An Adaptive Model for Digital Game Based Learning

Larkin Cunningham
BSc, MSc
orcid.org/0000-0001-5676-2299

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Head of Department: Dr Orla Murphy

Supervisors: Dr Orla Murphy
Dr Michael Cosgrave

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List of Abbreviations

4DF Four Dimensions Framework

ADDIE Analysis, Design, Development, Implementation and Evaluation

AI Artificial Intelligence

AMDGBL Adaptive Model for Digital Game-Based Learning

API Application Programming Interface

CAVE Cave Automatic Virtual Environment (Note: this is a recursive acronym)

CI Continuous Integration

CIT Cork Institute of Technology

DevOps Development and Operations

DGBL Digital Game-Based Learning

ERD Entity Relationship Diagram

GBL Game-based Learning

GM Game Mechanic

GOM Game Object Model

HMD Head Mounted Display

ICT Information and Communication Technology

ISD Instructional Systems Design

JPA Java Persistence API

JSON JavaScript Object Notation

LA Learning Analytics

LAD Learning Analytics Dashboard

LIE Learner Interaction Event

LM Learning Mechanics

LM-GM Learning Mechanics - Game Mechanics

MDA Mechanics, Dynamics and Aesthetics

ML Machine Learning

MVC Model-View-Controller

NLP Natural Language Processing

NSGM Narrative Serious Game Mechanics

PAL Personalised Adaptive Learning

REST REpresentational State Transfer

SAM Successive Approximation Model

SCL Student-centred Learning

SG Serious Games

SGM Serious Game Mechanics

SOLO Structure of the Observed Learning Outcome

SQL Structured Query Language

STEM Science, Technology, Engineering and Mathematics

TEL Technology Enhanced Learning

UCC University College, Cork

UD Universal Design

UDI Universal Design for Instruction

UDL Universal Design for Learning

UE4 Unreal Engine 4

VIMS Visually Induced Motion Sickness

VR Virtual Reality

ZPD Zone of Proximal Development

I, Larkin Cunningham, certify that this thesis is my own work and has not been submitted for another degree at University College Cork or elsewhere.

Larkin Cunningham

Abstract

Digital Game-based Learning (DGBL) has the potential to be a more effective means of instruction than traditional methods. However meta-analyses of studies on the effectiveness of DGBL have yielded mixed results. One of the challenges faced in the design and development of effective and motivating DGBL is the integration of learning and gameplay. A game that is effective at learning transfer, yet is no fun to play, is not going to engage learners for very long. This served as the motivation to devise a systematic approach to the design, development and evaluation of effective and engaging DGBL.

A comprehensive literature review examined: how games can be made engaging and how the mechanics of learning can be mapped to the mechanics of gameplay; how learning can be designed to be universal to all; how learning analytics can empower learners and educators; and how an agile approach to the development of instructional materials leads to continuous improvement. These and other considerations led to the development of the Adaptive Model for Digital Game Based Learning (AMDGBL).

To test how successful the model would be in developing effective, motivating and universal DGBL, a Virtual Reality (VR) game that teaches graph theory was designed, built and evaluated using the AMDGBL. An accompanying platform featuring an Application Programming Interface (API) for storing learner interaction data and a web-based learning analytics dashboard (LAD) were developed. A mixed methods approach was taken for a study of learners (N=20) who playtested the game and viewed visualizations in the dashboard. Observational and think aloud notes were recorded as they played and gameplay data was stored via the API. The participants also filled out a questionnaire. The notes taken were thematically analysed, and the gameplay data and questionnaire responses were statistically analysed. Triangulation of data improved confidence in findings and yielded new insights.

The learner study became a case study for a second, qualitative study of DGBL practitioners (N=12). The VR game was demonstrated and a series of visualizations presented to the participants. They then completed a questionnaire featuring open questions about: the need for the model; the benefits of VR; and the embedding of learning analytics, universal design for learning, iteration with formative evaluation, and triangulation at the heart of the model. The responses were thematically analysed.

The results of both studies supported the following assertions: that the AMDGBL would allow for iterative improvement of a DGBL prototype; that employing the AMDGBL would lead to an effective DGBL solution; that the inclusion of UDL would lead to a more universally-designed game; that the LAD would help learners with executive functions; and that VR would foster learner autonomy.

For Caroline and Conor

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I would like to express love and gratitude for my wife, Caroline, and my young son, Conor. Caroline's support in the final months as the hours grew longer and longer was vital. Conor was born just four weeks before I began the PhD and he has been a constant source of entertainment and hugs. I would also like to acknowledge the support of my parents and siblings.

I would like to acknowledge the support I have received from my employer, Cork Institute of Technology. I would not have been able to fund this PhD myself and I hope to see their investment in me returned many times over in the coming years. A special thanks to Dr. Noel Barry, now recently retired, who offered encouragement throughout. I would like to thank everyone in the Technology Enhanced Learning department for facilitating me as I carried out my studies.

Finally, I would like to thank everyone who participated in the studies. You gave so generously of your time (often a lot longer than advertised!) and provided me with such rich data to analyse. Researchers like me need people like you to volunteer. You did not have to and you deserve a special thanks for doing so.

A Personal Narrative and Reflection

Vivian Gornick (1935–), an American memoirist, emphasises the importance of a personal narrative when she writes in *The Situation and the Story: The Art of Personal Narrative* (2001):

> A serious life, by definition, is a life one reflects on, a life one tries to make sense of and bear witness to. The age is characterized by a need to testify. Everywhere in the world women and men are rising up to tell their stories out of the now commonly held belief that one's own life signifies.

As Nash (2019, p.24) puts it when analysing Gornick's quote: "your own life has meaning, both for you and others". "Your own life tells a story", he continues, "that ... can deliver to your readers ... moments of self and social insight that are all too rare in more conventional forms of research."

While most scholarly writing is written in a detached way, eschewing the *I* in favour of *the author* or *the researcher* (as the rest of the thesis does), the personal narrative is important for this reason: it can provide the reader with a sense of where the author is coming from and it can inform the reader about some of the choices made by the author—it can speak to the author's motivations and philosophy. In that spirit, the *I* is embraced here to tell a scholarly version of the author's story that informs the motivation for this thesis and some of the choices made in constructing it.

I was a child of the seventies and the eighties when the home computer revolution was beginning. Tom Lean's book, *Electronic Dreams: How 1980s Britain Learned to Love the Computer* (2016), does an excellent job of telling the story of those volatile years of many competing platforms eventually losing out to the *Personal Computer*. I played video games on my cousins' Amstrad computers before I was finally given a Commodore 16 as a Christmas present by my parents in 1985 when I was 11 years old. It's available RAM (random access memory) of 12 KB was only a fraction of what it would take to store this thesis's words (the LaTeX file for this thesis, containing raw text, is more than 600 KB). Yet, I can never remember being more excited before that moment, and rarely since, at playing what would now be considered very primitive video games. I was hooked. From that moment, all I wanted to grow up to be was a video game programmer. I programmed crude text adventure games in the BASIC programming language with lots of if-else statements. I borrowed computer books from the library and painstakingly entered line after line of code in the hope it might actually run so that a tiny game could be played. I upgraded my computers: a Commodore 64, an Amiga 500, an Amiga 600 and finally an Amiga 1200 with an enormous (for the time) 2 MB of RAM and a 170 MB hard drive. I still have that Amiga 1200 from 1992 in its original box, ready to pass on to my young son when he is deemed old enough not to break its now delicate parts. I hope, through him, I might rediscover some of that childish magic I experienced in those formative years.

One could say I achieved half of my original dream: the *programmer* bit, but not the *video game* bit. I went on to study computer science and graduate. In my final year of college, *Quake* appeared in one of the computing labs and many hours were lost to the early days of multi-player gaming—this phenomenon is recounted in another excellent book about video games and specifically the creators of *Quake*, David Kushner's *Masters of Doom: How Two Guys Created an Empire and Transformed Pop Culture* (2004). Before even graduating, I was offered a job as a junior programmer using the business-oriented programming language, COBOL. The world of IBM mainframes and insurance computer systems was far removed from the game console.

At that point, my dream job morphed into computer science lecturer, but it was many years (16) after graduation and several jobs as a software developer, and a detour as an entrepreneur, that this new dream eventually came to fruition as I got a foot in the door at Cork Institute of Technology (CIT) as a part-time lecturer, did reasonably well and was successful when interviewing for a permanent lecturing post. That was seven years ago.

Another detour I took prior to joining CIT was spending an amazing academic year at University of Edinburgh while completing a masters in creative writing. During this time I began what is currently my only novel. It would take several years before I completed the novel, *The Murk Beneath* (Cunningham 2016a), which I self-published when initial interest from literary agents petered out. It was an outlet for a creative side I had initially hoped would manifest itself in video game development.

When the opportunity of a fully-funded PhD arrived, I jumped at the opportunity to apply. CIT's staff doctorate scheme paid all course fees and removed a number of teaching hours from the timetable. It would take some time, however, to come to the realisation that the topic should combine all of the interests I have just outlined, but in a way focused on the direction my career had taken. As the years have gone by, it is clear that students are changing. They are becoming true *digital natives* (Palfrey and Gasser 2011). Attention spans, it seems, are dwindling and it is more difficult than ever to entice them into the classroom where the lecturer hopes something of value will take place because of the lecturer's presence. This modern angst was relayed by Dr. Greg Foley of Dublin City University (DCU) to a parliamentary committee in Ireland (O'Brien 2016). Students have a "highly distracting smartphone culture" and rely too much on material posted online (for example, to a learning management system) rather than attending in person, he told the committee.

Game-based Learning (GBL) looked promising as a way to engage students. A large percentage of teenagers play video games. One study, looking at secondary school students in Ontario, found that 85% of them played video games (Turner et al. 2012). Another, surveying similarly-aged students in America, found that 72% played video games (84% boys and 59% girls). A quick review of the literature on GBL (see Section 2.3) confirmed there was great potential in games for learning, but that it was largely being spurned by a lack of integration between gameplay and learning—in short, most game-based learning was just not fun enough.

My background in software development, and its systematic approaches to the development of software, along with my teaching interest in agile project management techniques (which are discussed in Section 2.6) and studies I had completed in pedagogy (such as module design and e-learning), eventually led me to frame my PhD research as one that would ultimately create a systematic model for the development of effective and engaging GBL solutions. Further study and research parallel to this PhD as part of a postgraduate certificate in effective teaching practice (an online portfolio is available on my blog[1]) showed that learning should be learner-centred and this further influenced my approach, such as including the universal design for learning (UDL) framework, which is discussed in Section 2.7.

And so it was that I had come full circle. I would finally become a video game programmer, but it would be in an applied way: to improve the engagement of my students. After all, the dream that I might some day program the new *Sim*

[1] See http://larkin.io/index.php/educ9042-portfolio/

City or *Bubble Bobble* and make millions was fanciful at best, but there is arguably a higher purpose in developing video games that engage learners.

This doctoral research has been quite a journey (yes, the word is a cliché, but it is apt in the context of a PhD). But it was a journey built on a previous journey, as outlined above, with all of the human capital I brought to the table, as Schultz (1961) might have put it. It has been an apprenticeship in DGBL and has added enormously to my skills set with respect to research and to facilitating student-centred learning, not just with DGBL, but in all other aspects of teaching and learning. Numerous avenues have been opened up and will be pursued in the years to come.

I look back at the research done and the thesis written with a mixture of pride for reaching the end of that part of the process, but also a realisation that there is still so much to learn. I look back months or even years at some of the work done and I can pick holes in it and wish I had done certain things that would have saved time or improved the quality of the research. To many, a PhD is a serious commitment in time and represents the summit of educational attainment, but it is only the beginning.

Chapter 1

Introduction

1.1 Background

Digital Game Based Learning (DGBL) has the potential to improve student learning experiences and outcomes when compared with traditional teaching methods (Boyle et al. 2016, Erhel and Jamet 2013, De Gloria et al. 2012, Connolly et al. 2012, Bellotti et al. 2010, Van Eck 2006). However, the effectiveness of DGBL is open to question with some meta-analyses showing DGBL to be more effective than traditional instructional methods, while others show differences that are not statistically significant (All 2017). The motivation for the research in this thesis, therefore, is to develop and evaluate a systematic method for the design and development of effective and motivating DGBL.

When devising a title for this thesis, the intention was to capture some of the essence of student-centred teaching and learning. The word *adaptive* can have several meanings depending on context, such as:

- Teachers and lecturers must adapt to their students.
- Instructional designers must adapt to what is discovered when piloting prototypes of instructional materials.
- Learners should be able to adapt their learning immediately based on prompt feedback.
- Learners should be given the tools to adapt their future learning based on past learning experiences.

- With recent advancements in artificial intelligence and machine learning, it is now possible for the instructional materials themselves (digitally based) to adapt to each learner.

Another way of stating that something adapts to all is to say that it is universal. If a learner presents with a disability, where possible that learner should be accommodated—in other words, educators should try to adapt to the needs of that learner. However, universal design is about designing for everyone, not just those with a disability (Gargiulo and Metcalf 2016), and so a universally-designed game should be one that empowers all learners.

Digital platforms allow for fine-grained data to be gathered. Every learner interaction with digital instructional materials can be captured for later analysis and visualization, but also be used for automated alerts and to react in real-time to the learner (Beer et al. 2014). It is data that underpins the areas of learning analytics, dashboards and adaptive learning.

However, none of the above matters if a game falls flat on its face—in other words, while it might be effective for learning transfer, if it is dull and does not motivate the learner, the learner will not use it. Therefore, the effective integration of learning and gameplay is vital (Arnab et al. 2015).

In researching a way of facilitating learning through a digital platform, this researcher takes a philosophical position that technological solutions to human problems should come into being through social activity, rather than treating technology as a black box that magically descends from the skies, never to be questioned, as might happen with an essentialist or instrumentalist disposition. This is what Hamilton and Friesen (2013) calls a *sociotechnical* perspective, a constructivist view of technology and not so much its relation to society, as if it were something to be considered separate, but a marriage of the two in a social process.

1.2 Methodological Statement

To complete the research objectives and answer the research questions a comprehensive multi-disciplinary literature review was carried out. This involved exploring the literature in areas such as pedagogy, developmental psychology, game-based learning, computer science and universal design. With the review of literature complete, it was possible to identify the components and processes of the AMDGBL. To help evaluate the AMDGBL, a VR-based game being designed, developed and formatively evaluated using the model. An accompanying platform was also developed to allow captured gameplay data to be stored centrally for analysis and visualization. A mixed methods study, employing observations, think aloud, questionnaire and gameplay data analytics, was used to evaluate how effective the VR game was in teaching learners the fundamentals of graph theory and how well the game performed from a universal design for learning perspective. Triangulation was employed to improve confidence in the findings and discover new insights. The output from the learner study (which became a case study) was used as input to a second study, which was a qualitative one employing a thematic analysis of response data to a questionnaire featuring open questions about the benefits of virtual reality, the need for the AMDGBL, and the value of the elements (such as iteration, universal design for learning and learning analytics) embedded in the AMDGBL. The findings from both studies were used to answer the research questions.

1.3 Contributions to Knowledge

The following contributions to knowledge were made as a result of the research for this thesis.

1. A new model for the development of digital game-based learning, the Adaptive Model for Digital Game Based Learning (AMDGBL), is arguably the most comprehensive published model, incorporating agile approaches to instructional design and development (frequent iteration with functional prototypes evaluated by key stakeholders) with a framework and suggested tools (models, lenses or frameworks) for the formative and summative evaluation of different aspects of a learning game. This includes incorporating universal design at the heart of the model, embracing learning analytics with learning mapped to data points (or learner interaction events), along with suggested models for evaluating how the learning game being developed maps learning mechanics to the game's mechanics and dynamics, and how effective the game is from a learning outcome, motivation and efficiency standpoint.
2. The learning analytics platform, incorporating an application

programmer interface (API) and web-based dashboard, is a significant improvement in the way both formative and summative evaluation can be performed by DGBL practitioners, and allows learners perform executive functions (such as through metacognition, goal setting and planning). While it is not entirely unique, it has some differences to the other similar platform identified, RAGE Analytics, and these will make it a more appropriate choice for some projects (as discussed in Section 4.3).

3. The VR-based learning game, The Graph Game, is a novel and new way of teaching graph theory that was shown to be effective and fostered learner autonomy. By sending learner interaction data from the game's engine to the learning analytics platform, it was possible to further gamify the learning with badges and leaderboards, adding a social dimension to the game, and give learners feedback on how they were progressing at a global level (that is, from a formal learning outcome perspective) or immediately in-game with audio and visual cues or metaphors.

4. The game mechanics developed for The Graph Game could be widely deployed for DGBL, simulation or visualization. Interconnectedness is at the heart of many concepts in mathematics, science, business, the humanities and more. The Graph Game's mechanics are novel and can be re-purposed for a new context.

5. The methodology in the study of learners is comprehensive with multiple methods employed, allowing for triangulation of data to identify new insights and increase confidence in existing findings. It shows how to bring best practice from the video games industry into the game-based learning arena.

6. It was shown that a VR-based game that allows for significant locomotion in a large and immersive virtual environment, and allows for physical interaction with objects (in other words, kinaesthetic or tactile learning), fosters learner autonomy and several strategies were identified as learners completed exercises.

Boyer's (2015) widely used model (within academia) of scholarship can be used to frame the contributions in this thesis. The AMDGBL can be seen as fulfilling the scholarship of integration, in that it brings (or curates) elements from several disciplines into a single model. The graph game and platform can be seen as fulfilling the scholarship of application. The contributions to the knowledge on the evaluation of game-based learning solutions, as part of the learner study methodology, as well as the strategies observed in the VR environment of the game, could be said to fulfil the scholarship of discovery. The graph game also fulfils the scholarship of teaching and learning because of its rigorous approach to embedding theories of teaching and learning.

1.4 Publications Related to this Thesis

Cunningham, L.: 2016, A Serious Game to Dissuade Adolescents from Taking Performance Enhancing Drugs, in: Proceedings of the Collaborative European Research Conference, Cork, pp. 224-226.

Cunningham, L.: 2018, Using Learning Analytics to Improve Digital Game-Based Learning, in: *New Perspectives in Science Education Conference, 7th Edition*, Florence, pp. 177–181.

Cunningham, L., Murphy, O.: 2018, Embracing the Universal Design for Learning Framework in Digital Game Based Learning - A Set of Game Design Principles. Transforming our World Through Design, Diversity and Education, *Studies in Health Technology and Informatics* 256, pp. 409–420.

Cunningham, L.: 2018, A Virtual Reality Game for Teaching Graph Theory: A Study of its Effectiveness in Improving Outcomes and Encouraging Autonomy, in: *Proceedings of the 11th Annual International Conference of Education, Research and Innovation*, Seville.

Cunningham, L., Murphy, O.: 2019, A Qualitative Study of Practitioner Perspectives on the Design and Development of Effective Game-based Learning Solutions, in: *Proceedings of the 11th International Conference on Education and New Learning Technologies*, Palma, pp. 9191-9199.

1.5 Structure of the Thesis

Chapter 1 puts the research in context. It also highlights the contributions to knowledge of the research and how the research was disseminated to the wider research community through publications.

Chapter 2 is a literature review that explores play and games, digital game-based learning, virtual reality, teaching and learning, agile software development, universal design for learning and the use of data to assist learners and educators. It concludes with the research questions and objectives derived from the review.

Chapter 3 presents the Adaptive Model for Digital Game Based Learning based on what was uncovered in the literature review.

Chapter 4 describes the methodology and the technologies used to design, build and evaluate the VR-based graph game and the DGBL platform that incorporated an application programming interface for the central storage of learner interaction data and a web-based dashboard for the visualization of learning.

Chapter 5 details the two studies carried out, describing the methodology employed, the design of the studies, ethical considerations, recruitment of participants, how the studies were carried out, how the data was analysed, the findings of each study and how they map to the research questions. The first is the learner study employing a mixed methods approach and the second is the practitioner study employing a qualitative approach.

Chapter 6 provides a more detailed summary of the thesis and discusses how the research met its objective and answered its questions. Limitations of the research are outlined and possible future work identified.

Chapter 2

Literature Review

2.1 Introduction

The aim of this thesis is to develop an adaptive model and a platform for DGBL. The following chapter explores relevant literature that underpins the development of the model in Chapter 3.

This chapter begins with Section 2.2 about play and games. The concepts of play and games are fundamental to digital game-based learning (DGBL).

Section 2.3 investigates DGBL. It covers what DGBL is and how it can be made engaging. The effectiveness of DGBL is discussed as well as how to evaluate DGBL in terms of effectiveness and what types of learning are taking place. The section concludes with very recent examples of DGBL in action.

Section 2.5 explores teaching and learning, including theoretical perspectives on teaching and learning, and instructional design models and frameworks.

Section 2.6 is concerned with agile software development, which outlines the principles and practices underpinning how high-quality software (including DGBL) can be developed.

Section 2.7 is about universal design (UD), which discusses how teaching and learning can be designed for all learners with the help of UD principles and frameworks.

Section 2.8 explores the emerging fields of learning analytics, which uses data to gain insights into the way students learn and identify students in need of intervention, and artificial intelligence, which can provide personalised adaptive learning.

2.2 Play and Games

As humans evolved from primates (and other mammals evolved into primates), brain size increased such that babies were born increasingly immature and requiring longer nurturing time; this longer nurturing time was accompanied by an increase in playfulness (Bruner 1972).

There are clear links between playfulness and cognitive and emotional development (Burriss and Tsao 2002). Tamis-LeMonda and Bornstein (1989) showed that infant habituation was a predictor for the level of a child's later level of symbolic play (which is pretend play, such as pushing a block on the ground to represent a car). Bornstein (2006) found that complex play, such as symbolic play, was correlated with improved emotional well-being. Play contributes to child or adolescent development from a cognitive, social, physical and emotional well-being standpoint (Ginsburg 2007). Vygotsky (1978) found that play contributes significantly to language development and self-regulation—the link between language and the development of self-regulation is strong (Vallotton and Ayoub 2011, Petersen et al. 2015).

There are many theories about why children play. The following list presents some of them, not intended to be comprehensive, but to give a sense of how varied the theories are.

Surplus energy theory: A child builds up an excess of energy through the day and active play is required to get rid of that surplus energy. An example is when children sit in class, thereby acquiring surplus energy, and require break time to expend the superfluous energy (Evans and Pellegrini 1997).

Recreation theory: Play is a way to recuperate from fatiguing hard work. Play has a restorative effect and is of more benefit to the body than being idle (Mitchell and Mason 1948).

Pre-exercise theory: Groos thought that play was a way for children to practice behaviours that were essential for survival in the wild and that this has carried forward to modern times (Groos 2018).

Recapitulation theory: Haeckel's biogenetic law states that organisms recapitulate the history of a race from the moment the egg starts growing (MacBride 2009). Building on this, G. Stanley Hall argued that the development of the child into an adult mirrors that of the evolution from primitive human to the human of the current time—therefore the play of the child, such as beating a stick off a tree, is similar to the actions of savage man (some of Hall's language is controversial, such as his use of terms like "low races" and how they are at the level of children or adolescents) (Green 2015).

Freud's cathartic play: Sigmund Freud considered play to be cathartic, a way for children to work out their negative emotions and to replace them with positive ones (Burriss and Tsao 2002).

Piaget's cognitive theory: As the child develops through stages, the limitations of motor and cognitive ability at each stage dictates how different concepts can be accommodated and assimilated—from the sensory-motor to the mental (Piaget 1952).

The words *play* and *games* are often used interchangeably, though games can be said to give form to play (Klabbers 2006). Johan Huizinga in *Homo Ludens* (1949) described play as something that is "isolated" or "hedged around", even "hallowed", where special rules apply. Magic circles, he writes, are "temporary worlds within the ordinary world". Klabbers (2006) describes the playing of a game as "a total event of being involved in a temporary, provisional, and integrated world."

In explaining the concept of the magic circle, Adams (2013) contrasts the magic circle with the real world. The real world contains real world concepts, situations and events, whereas the magic circle contains game concepts, situations and events. He gives the example of a game of soccer where in the real world, the situation is a field with the event of a ball being kicked into a net; in the magic circle this is the scoring of a goal.

The concept of the magic circle, it appears, involves an invisible barrier between the real and the game worlds. However, Egenfeldt-Nielsen et al. (2016) provide some criticism of this concept: games require time, affect our mood and behaviour, can be a communication medium, and so therefore can directly affect the outside world.

Caillois (2001), in *Man, Play and Games*, first published in French in 1958, offers a criticism of Huizinga's magic circle, partly because Huizinga's definition involves secrecy and mystery (Huizinga uses words like *hallowed* and *forbidden*), making his definition too broad, but also because he finds Huizinga's definition of play too narrow—games of chance or games lacking rules are excluded.

Caillois describes play as something that is voluntary, uncertain, unproductive and consists of make-believe. He provides four categories of game:

- Agon (competition)
- Alea (chance)
- Mimicry (mimesis, imitation, role playing)
- Ilinx (a *whirlpool*, inducing vertigo or altering perception)

The categorisations are too neat in isolation. For example, if one considers the game of poker, there is an element of competition (agon) and chance (alea). The more skilful the player (in bluffing, for example), the less that the element of chance matters to the player. The game of *Dungeons and Dragons*[1] overlaps competition (there are multiple participants in the game), chance (dice are rolled) and role playing (players can be wizards, warriors, and so on). It is obvious from these examples that games can overlap two or more categories.

Caillois further introduces the continuum of *Paidia* (loose, childish play, amusement) to *Ludus* (rigid rules). Poker, for example, is much closer to Ludus than it is to Paidia. A game like pin the tail on the donkey would be much closer to the Paidia end of the continuum.

Roberts and Sutton-Smith (1962) approach the study of games from a cultural perspective. Games are what they call "systematic culture patterns" that are widely spread throughout the world's cultures. This suggests that the great majority (the authors note that a small number of cultures do not appear to have games according to their definition of games) of cultures will be familiar with the concept of a game. However they found that cultures vary widely—some, for example, may have games of skill, such as those based on fighting or weight lifting, but have no strategy games. In short, Sutton-Smith writes that as societies advance and become more complex, so do their games (Egenfeldt-Nielsen et al. 2016).

[1] http://dnd.wizards.com/

Games are also a way for children to engage in role playing. George Herbert Mead (1925) writes that children attain self-consciousness in two stages: play and then games. Children play the roles of “policeman” or “Indian”. Mead distinguishes between play and games: a game, he writes, features a “regulated procedure, and rules” and this distinguishes a game from play because the child not only assumes the role of an other, but also assumes the other various roles in the game (children assimilate the responses of the other roles and this governs their actions accordingly).

This type of role playing has extended into adolescence and adulthood through the medium of the video game. For example, squad-based multiplayer online games like *Team Fortress 2* (Valve 2007) require the player to choose a role, such as an assassin, and cooperate with fellow squad members who have assumed other roles. Tim Schafer, developer of the games *Grim Fandango* and *Psychonauts*, said that all games are wish fulfilments to some degree and asks why players would play a character in a game that was “not as cool” as themselves (Pearce 2003).

One of the more formal definitions of what a game is is provided by Bernard Suits (1967) and pre-dates the video game industry and the term ludology, which is now used to identify the discipline of game studies:

> [T]o play a game is to engage in activity directed toward bringing about a specific state of affairs, using only means permitted by specific rules, where the means permitted by the rules are more limited in scope than they would be in the absence of the rules, and where the sole reason for accepting such limitation is to make possible such activity.

Some noted experts or authors on video games have defined games in various, more accessible, ways, though with some common features, such as rules and outcomes.

Salen and Zimmerman (2003) A game is a system in which players engage in an artificial conflict, defined by rules, that results in a quantifiable outcome.

Juul (2003) A game is a rule-based formal system with a variable and quantifiable outcome, where different outcomes are assigned different values, the player exerts effort in order to influence the outcome, the player feels attached to the outcome, and the consequences of the activity are optional and negotiable.

Sid Meier A game is a series of interesting choices (Rollings and Morris 2000).

Juul's definition is an attempt at an all-encompassing definition. Salen and Zimmerman have a more closed defintion concerned with conflict and fixed outcomes. Both are close to Caillois's *Ludus* concept, as is Suits's defintion, which is explicit about games having rules in contrast to looser activities lacking rules. Meier's definition is by far the loosest and implies that games are concerned with agency—allowing the player decide where the game goes. Agency allows players to be more engaged in a game because they have a greater level of control over what happens in a game and thus make the narrative in a game their own (Rigby and Ryan 2011). However, the degree of agency is limited by a game's rules or the "illusion of control" (Langer 1975) a game might give a player.

In an attempt to make it easier to place a game (or not a game) on a continuum from *game* to *not game*, Juul (2003) provided a model of game definitions (which he simply called "The game diagram"). It cannot be said to be a continuum—Juul is explicit about what characteristics make something a game, not a game, or something that is borderline. Definitively not a game includes free-form play, hypertext fiction, ring-a-ring-a-roses; definitively a game includes games that have all of the six elements in his definition, which are:

1. Fixed rules
2. Variable outcome
3. Valorization of outcome
4. Player effort
5. Player attached to outcome
6. Negotiable consequences

According to Juul, borderline cases are missing one or two of these essential game elements. For example, pen and paper role-playing lacks fixed rules and games of pure chance lack player effort.

Juul provides an interesting example of another borderline case: *Sim City*[2].

[2]see https://www.theregister.co.uk/2013/02/22/feature_antique_code_show_simcity for an overview of the classic version

The game lacks explicit goals (therefore lacking "valorization of outcome"). Juul places it in the category of *open-ended simulation*. According to Juul, therefore, a simulation is not a game.

However, some software titles that identify with the term *simulator* also identify with the game concept. This perhaps depends on the level of seriousness of the software. *Goat Simulator*, for example, self-identifies as "a small, broken and stupid *game*"[3]. *Surgeon Simulator* identifies as a "sim game"[4]; this contrasts with a peer-reviewed article on a cataract surgery virtual reality simulator (Selvander and Åsman 2012) where the word game is not mentioned in the main text, despite there arguably being a "valorization of outcome" (a successful operation).

Simulations are particularly interesting in terms of the VR game developed for this thesis. Simulations or "sim games" are by far the most common type of game in serious games for learning (Connolly et al. 2012, Boyle et al. 2016).

2.3 Digital Game Based Learning

2.3.1 Overview

Digital Game Based Learning (DGBL) is under the umbrella of the term *Serious Games* (Egenfeldt-Nielsen et al. 2016). While most serious games tend to be for the purposes of education, whether considered as another form of instructional materials, or to raise awareness, such as with *games for change*, other serious games promote products (advergames) or persuade in other ways, for example politically (Bogost 2007).

Serious games can cross boundaries—the *McDonald's Videogame* is educational in terms of how it teaches about supply chains in the food service industry (one could map out such learning outcomes); but it is rhetorical in the sense that it attempts to be persuasive against practices such as intensive farming; this is an example of what Bogost terms the *anti-advergame* (2007, p.29).

Much of the literature on serious games and DGBL use the terms interchangeably. Egenfeldt-Nielsen et al. (2016) offers a comprehensive list of

[3]According to the disclaimer at http://www.goat-simulator.com/ - emphasis on the word game added

[4]https://www.bossastudios.com/games/surgeon-simulator/

labels for serious games, which one might consider subgenres, each with particular nuances:

- Gamification (which is an embedded form of gaming, rather than a pure gaming platform)
- Game-based learning
- Educational computer games
- Edutainment
- Advertainment
- Corporate Games
- Health games
- Military games
- Games-for-change
- Political games

The title of this thesis elects to prepend the word *digital* to game-based learning to distinguish its focus from non-digital games based around boards, cards and other media. DGBL allows for automation and the collection of data, which will play important roles in the model.

Clark C. Abt is considered the person to have coined the phrase serious games. Early in his book, *Serious Games* (Abt 1970), which largely pre-dates the video game era, he writes that serious games

> "have an explicit and carefully thought-out educational purpose and are not intended to be played primarily for amusement."

He identifies fields in which serious games are applicable, such as "[e]ducation, industrial and governmental training, planning, research, analysis, and evaluation." He further writes that serious games "unite the seriousness of thought and problems that require it with the experimental and emotional freedom of active play."

Serious games are games which have education (in its various forms) as the primary goal instead of entertainment, though that does not mean that they should necessarily be solemn experiences lacking in entertainment (Abt 1970, Michael and Chen 2005, De Gloria et al. 2012). However, games intended primarily for entertainment purposes can also contain serious game elements—that is to say, they are good for learning (Gee 2014).

Serious games have seen rapid growth for more than a decade in both academia and industry, in areas such as education and cultural heritage, well-being and health care, and they have huge potential in improving achievements in these areas and others (Laamarti et al. 2014, De Gloria et al. 2012). Industry analysts, such as Gartner and IDATE predict significant growth in the serious games market in the short to medium term (IDATE specifically predicted growth of the market from €4.5 billion in 2014 to €11.7 billion in 2018) (Egenfeldt-Nielsen et al. 2016).

Deterding (2012) puts it succinctly when he writes that serious games are games that "train, educate, and persuade." However, Bogost (2007) has questioned the use of the term "serious game", arguing instead for "persuasive game", which distinguishes the games from often classroom-based game-based learning.

Other largely interchangeable terms abound. The terms *games for impact*, *impact games* or more specifically *societal impact games* are also used to describe games that change player attitudes towards societal challenges like climate change, immigration and poverty. "Transformational games" are what game designer Jesse Schell calls "serious games, but fun" (Games for Change 2016)—this is perhaps unfair given that many serious games try to manage the difficult task of combining entertainment and effectiveness with varying degrees of success.

2.3.2 Effectiveness of DGBL

Much of the early research on video games concentrated on the negative aspects of playing them, such as increases in aggressive thoughts, inability to regulate time spent playing, addiction and social isolation (Connolly et al. 2012). However, there have recently been studies on the positive effects of video games on children and adolescents, such as improved problem-solving skills, school competence, high intellectual functioning and intergroup relations (Kovess-Masfety et al. 2016, Adachi and Willoughby 2017).

There are several studies which show that games have potential as a learning tool to enhance a learner's experience (including learning and motivation) when compared with more traditional teaching approaches (Boyle et al. 2016, Erhel and Jamet 2013, De Gloria et al. 2012, Connolly et al. 2012, Bellotti et al. 2010, Van Eck 2006). Some meta-analyses show DGBL to be more effective than traditional instructional methods, but others show differences that are not statistically significant (All 2017). As Erhel and Jamet (2013) note, there have been questions about the compatibility of games with deep learning—the authors themselves found in a study that when regular feedback about performance is given, the learning is deeper.

Connolly et al. (2012) was, at the time, the most significant study on the positive effects of video games and serious games on the impacts and outcomes of them. 129 papers published between 2004 and early 2009 and based on empirical evidence about serious games and their impacts and outcomes (such as positive behavioural change and learning outcomes) were examined. A huge variety in terms of methodology and results was found and this reflected the view of Ke (2009) that the literature on the impacts and outcomes of games is fragmented and at times incoherent. There were relatively few studies that employed randomized controlled trials, which Connolly et al. rated highly.

Connolly et al.'s research was updated by Boyle et al. (2016) because as the authors noted, the literature in the research of games dates very quickly. The authors, examining papers published between 2009 and 2014, found a marked increase in the number of papers reporting positive impacts of games (512 versus 129) in the same period of time (5 years). However, there was little difference in the quality of the research, showing that while there is an increasing interest in researching games for their positive effects, the increasing number of researchers in the area have perhaps not learned from exemplars in the field.

In relation to specific subject areas, DGBL was found to be effective in terms of learning outcomes and engagement in science, particularly when it is conceptually integrated (Clark et al. 2011). It is no surprise, then, that STEM and health (which is a largely scientific field) were the most popular subjects in terms of adoption of games for learning in Boyle et al. (2016). The game developed for this thesis fits neatly in the STEM category and the design of its mechanics and dynamics aimed for conceptual integration, such as the dynamics of graph completion.

2.3.3 Making Games Engaging

Making games engaging is another way of saying making games fun (the term aesthetics is used in place of fun in the subsection on the MDA framework). Two approaches to game design and analysis are covered: the MDA framework allows games to be constructed (or deconstructed) in terms of their mechanics, dynamics and aesthetics; then the less tangible elements of flow and balance are considered. Both approaches address the important gameplay aspects of experience and focus. To put it another way, that the game is fun and keeps the player from getting too bored or frustrated (that is to say, keeping the player engaged). The section continues with a discussion of motivation and how gamification can be used to embed game elements in non-game contexts, thereby making those non-game contexts more engaging. The section concludes with a discussion of narrative as it relates to video games.

2.3.3.1 Mechanics, Dynamics, Aesthetics and Dramatic Tension

The MDA (Mechanics, Dynamics, Aesthetics) framework (Hunicke et al. 2004) is often used as a tool to help with the design of games, but also to analyse existing games. It allows for game design and player experience to be considered at the same time (Kim 2015).

Mechanics are the low-level elements of a game, such as player movements, game engine algorithms and data structures. Sicart (2008) defines mechanics as “methods invoked by agents, designed for interaction with the game state”. In isolation, mechanics do not amount to anything, but when they are employed at run-time in a game, they are the building blocks of game dynamics—how the game plays, in other words. The game dynamics are what create the game’s aesthetics, or the desired “emotional responses evoked in the player” (Hunicke et al. 2004).

Aesthetics is rooted in the old Greek word aisthesis, meaning an “understanding through sensory perception” and while aesthetics is often associated with the visual, it equally applies to the non-visual and is not restricted to works of art, nor is it simply a matter of styling (Hekkert and Leder 2011). In the eighteenth century, the concept began to take on the meaning of “sensory pleasure and delight” (Goldman 2001). It is primarily in the latter sense of sensory pleasure that aesthetics is used here.

The MDA framework authors identify eight aesthetics (see Table 2.1), while noting that their list is not exhaustive. Multiple aesthetics can apply to a single game, each to a greater or lesser extent. No one particular aesthetic can be said to make the game fun, rather it is the combination of a multitude that hopefully makes the game a worthwhile experience where the transfer of learning, or the transmission of a rhetoric for the purposes of persuasion, is not seen as a chore for the player.

Table 2.1: MDA Framework - Eight Aesthetics

Sensation - *Game as sense pleasure*	**Fellowship** - *Game as social framework*
Fantasy - *Game as make-believe*	**Discovery** - *Game as uncharted territory*
Narrative - *Game as drama*	**Expression** - *Game as self-discovery*
Challenge - *Game as obstacle course*	**Submission** - *Game as pastime*

Reproduced from Hunicke et al. (2004).

The MDA authors use the MDA framework to analyse four popular games, one of which is not digital, from an aesthetic perspective:

Charades: Fellowship, Expression, Challenge.

Quake: Challenge, Sensation, Competition, Fantasy.

The Sims: Discovery, Fantasy, Expression, Narrative.

Final Fantasy: Fantasy, Narrative, Expression, Discovery, Challenge, Submission.

The developers of *Quake* (id Software) were vocal in eschewing narrative in favour of addictive game dynamics (Kushner 2004). *The Sims* allows players to express themselves by constructing characters with chosen attributes, to decide to create a family, and so on. As the name suggests, *Final Fantasy* allows the player to be immersed in a fantastical land unlike anything experienced before. The game of charades cannot be played alone and requires a group of fellow human beings.

When a game is analysed through the MDA lens, it is possible to see how the smallest game mechanic contributes to a game dynamic that emotionally engages the player. If there is not that link between a game mechanic and an aesthetic, its place should be questioned. Without emotional engagement, the player is likely to become bored (Schell 2015) and one of the central arguments for DGBL—that being fun motivates and improves learning—disappears.

Often underpinning sensation (the game as sense-pleasure) is *dramatic tension*, which according to Hunicke et al. "comes from dynamics that encourage a rising tension, a release, and a denouement". These peaks and troughs feature in what Csikszentmihalyi calls the flow channel, discussed in Section 2.3.3.2, which ensures that tension does not remain high for too long (leading to anxiety) or that there is not enough tension (leading to boredom or apathy).

2.3.3.2 Flow and Balance

The theory of flow is concerned with the intrinsic motivation of individuals to complete tasks. Mihaly Csikszentmihalyi studied a variety of people performing different tasks, such as playing chess, rock climbing and surgery (Csikszentmihalyi 1975, 1990). From his research it emerged that masters of a demanding skill, such as surgeons, were not motivated primarily by money or prestige, but by the exhilaration experienced when performing tasks that were just within their ability. He describes the tasks these people (masters) perform as being *autotelic*—*auto* being self and *telos* being goal. Tasks are undertaken for their own sake. An example is the climber climbing a mountain, not to reach the peak, but for the difficult and exhilarating climb that precedes it.

From his studies, Csikszentmihalyi developed a list of eight elements (Table 2.2) common to those people who enter into a state of flow, or who have an optimal experience. Both Cowley et al. (2008) and Pavlas (2010) map these eight elements to gameplay elements. Table 2.3 shows these mappings. The table can be used as a check-list against which to evaluate whether a game is likely to result in the player being in a state of flow.

A related concept is that of the flow channel (see Figure 2.1), which plots an ideal path based on skill level and the challenge faced to ensure the person is neither bored nor anxious. As Figure 2.1 illustrates graphically, if the challenge greatly exceeds the player's skill level, the player will enter a state of anxiety and exit the flow channel. If a "master" is faced with too easy a challenge, the person will become bored and again exit the flow channel. In either case, it will result in the person disengaging with the activity. When challenge is maintained consistently in the flow channel, the participant enters a state of

Table 2.2: Elements of Flow

A challenging but tractable task to be completed.
One is fully immersed in the task, no other concerns intrude.
One feels fully in control.
One has complete freedom to concentrate on the task.
The task has clear unambiguous goals.
One receives immediate feedback on actions.
One becomes less conscious of the passage of time.
Sense of identity lessens, but is afterward reinforced.

Reproduction of Cowley et al. (2008, Table I).

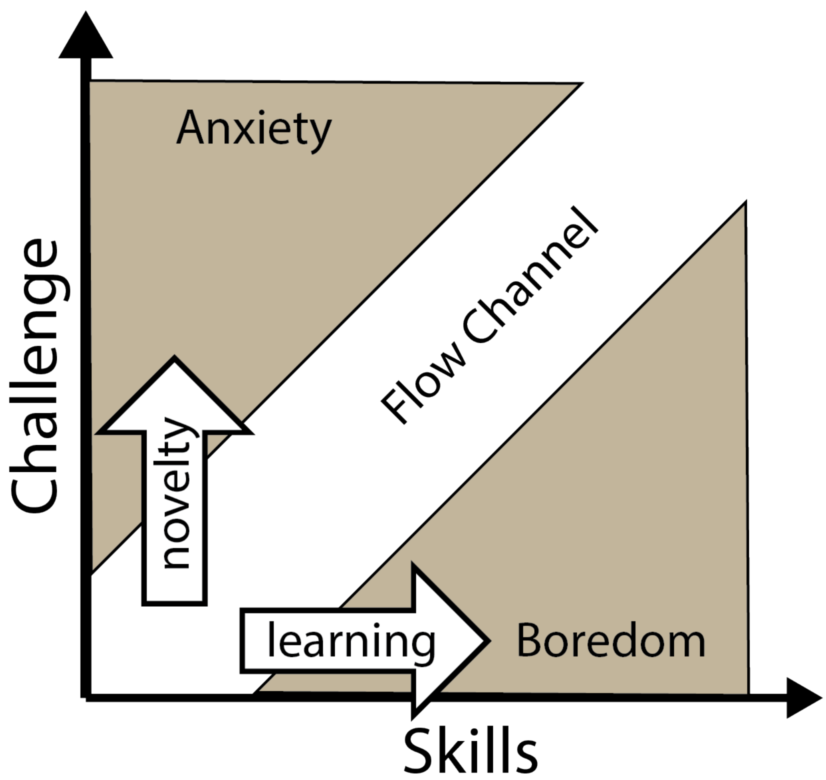


Figure 2.1: Three dimensions of experience, reproduced from Csikszentmihalyi (1990)

Table 2.3: Elements of Flow Mapped to Game Elements

Csikszentmihalyi	**Cowley et al. (2008)**	**Pavlas (2010)**
(1) A task to be accomplished	The whole gaming experience (including social interaction during game-play)	The game and the player's perception thereof
(2) The Ability to concentrate on a task	Telepresence and an environment dedicated to gaming	A task requiring concentration as well as an interface that does not impede it
(3) Sense of control over actions	Familiarity/skill with the controller, genre conventions, game-play mechanics	A sense of control is created when the player has a feeling of agency. For this to occur, the player's actions must have a salient effect upon the game's environment
(4) Deep but effortless involvement	High motivation to play, no imperative to do otherwise; empathetic to content	It is a result of unimpeded interaction with a skill-challenged tuned system that provides interesting choices
(5) Clear task goals	Missions, plot lines, levels; any explicit outcome of a successful play session	Make goals clear from an interaction-accordance standpoint or some sort of goal listing (e.g., the "quest log")
(6) Immediate feedback	Well-timed, suitable rewards and penalties	Effects of player performance should be evident (player's actions are transparent to the user)
(7) Being less conscious of the passage of time	Focusing on another, temporally-independent environment	The authors of this work argue these two elements describe immersion as an outcome of flow. This state describes a player's state of mind which is characterized by loss of concern for the self, an altered sense of time and a deep but effortless involvement
(8) The sense of identity lessens, but is reinforced afterwards	Embodiment in game avatar; sense of achievement after play, e.g. "Hi-Score"	

Reproduction of Arzate Cruz and Ramirez Uresti (2017, Table 3).

flow where external stimuli are less obvious and concentration on the task at hand increases.

The problem, however, is that as the participant begins to master the challenge presented, so the participant begins to drift out of the flow channel towards boredom. When it comes to video games, it is important to increase challenge as the player masters the game's mechanics (such as becoming familiar with the controls or recognising the patterns of attack of non-player characters) to reposition the player within the flow channel. However, doing so too quickly risks pushing the player off the other side of the channel and into frustration.

Schell (2015) offers an improvement on the linearity of the flow channel by introducing peaks and troughs (see the wavy line in Figure 2.2), similar to the concept of dramatic tension discussed in Hunicke et al. (2004). The player experiences cycles of: rising tension, followed by a release, followed by a denouement (or perhaps more accurately an end of level or cut scene). The denouement might include a power-up that increases the skill level of the player's avatar—it should be noted that skill levels of the player will rise through practice or can be artificially raised via the avatar.

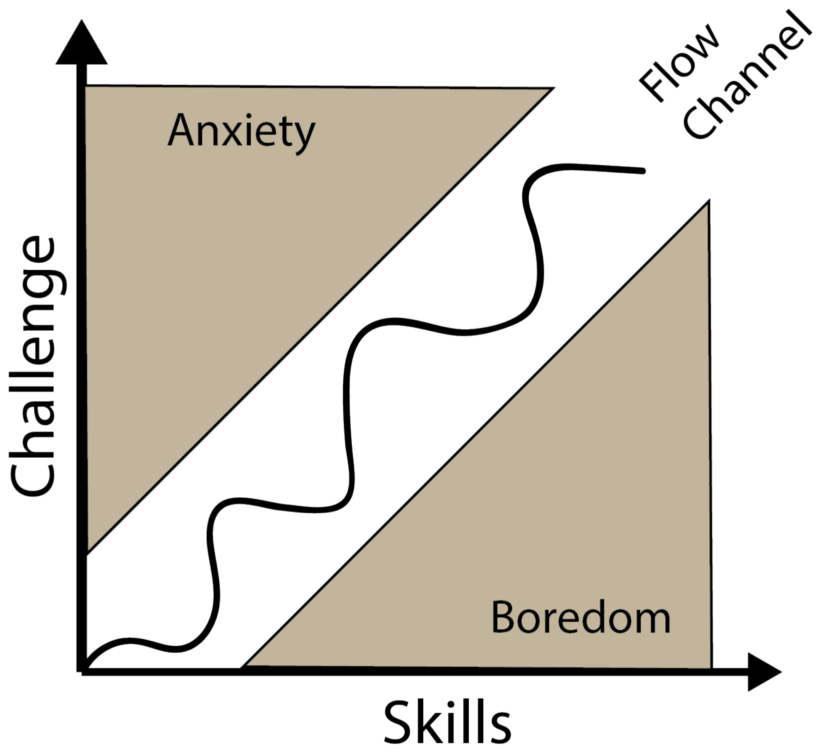


Figure 2.2: Three dimensions of experience with less linear flow.

The flow channel, as charted by Figure 2.2, can only be used as guidance—accurately measuring and plotting metrics for levels of boredom and anxiety as challenge and skill increases would be very difficult. When addressing *balance* in games, Schell (2015) provides a lens through which to evaluate the level of challenge in a game (see questions to ask in Table 2.4). Answering these questions somewhat addresses the values plotted to determine whether the player is in the flow channel—the questions concern level of challenge balanced against player skill.

Table 2.4: Schell's Lens of Challenge

What are the challenges in my game?
Are they too easy, too hard, or just right?
Can my challenges accommodate a wide variety of skill levels?
How does the level of challenge increase as the player succeeds?
Is there enough variety in the challenges?
What is the maximum level of challenge in my game?

From Schell (2015, p.209).

2.3.3.3 Motivation and Gamification

Video games have the potential to be highly motivational and it is not unreasonable to harness that potential for real-word uses (Sailer et al. 2017).

Malone (1981) offered three categories that make environments intrinsically motivating: *challenge*, *curiosity* and *fantasy* (challenge is addressed here, curiosity later in this section, and fantasy in the next section on narrative). According to Malone, challenge is generated by goals with uncertain outcomes. Malone's challenge category is closely related to Csikszentmihalyi's theory of flow and Schell's lens of challenge (discussed in Section 2.3.3.2). A challenge should have goals that are meaningful to the player and there should be feedback on how players are progressing towards those goals (Malone and Lepper (1987) found that explicit goals in a game highly correlated with children's preference for a game). Malone and Lepper also state that succeeding with a challenge increases a player's self-esteem, but constructive feedback on performance should be presented in a way that does not diminish self-esteem (or better yet, challenges should have a graded sequence of difficulty to allow players of all abilities succeed at their level).

Csikszentmihalyi offered a set of guidelines for creating intrinsically motivating activities (Table 2.5). As well as structuring activities to match challenges to skills, Csikszentmihalyi highlights feedback as being important so that the actor or player is aware of progress towards goals, for example. If the level of challenge is well matched with a player's skill level, yet the player is unaware that the goal is almost within reach (because of a lack of concrete feedback), then the level of frustration could grow disproportionately to progress, resulting in a premature exit from the flow channel.

Table 2.5: Guidelines for Creating Intrinsically Motivating Activities (Csikszentmihalyi 1978)

The activity should be structured so that the actor can increase or decrease the level of challenges he is facing, in order to match exactly his skills with the requirements for action.
It should be easy to isolate the activity, at least at the perceptual level, from other stimuli, external or internal, which might interfere with involvement in it.
There should be clear criteria for performance; one should be able to evaluate how well or how poorly one is doing at any time.
The activity should provide concrete feedback to the actor, so that he can tell how well he is meeting the criteria of performance.
The activity ought to have a broad range of challenges, and possibly several qualitatively different ranges of challenge, so that the actor may obtain increasingly complex information about different aspects of himself.

Schell (2015) provides two lenses through which to examine a game's motivational affordances: the lens of motivation (Table 2.6) and the lens of novelty (Table 2.7). With respect to motivation, Schell asks the game designer to question which motivations in the game will be intrinsic versus extrinsic, and which will complement each other versus conflict with each other. With respect to novelty (which he considers a significant motivator), Schell writes that a "successful game is a mix of the novel and the familiar." In other words, novelty alone is not enough and too much novelty, and a lack of other features, may not keep a player engaged.

Curiosity comes in two forms, according to Malone and Lepper (1987): sensory and cognitive. Sensory curiosity is stimulated by attractions in the environment, such as light and sound. Cognitive curiosity is stimulated by a drive to improve cognitive structures—one example is to present apparent inconsistencies; Malone and Lepper (1987, citing Morozova 1955) gives the

Table 2.6: Schell's Lens of Motivation

What motivations do players have to play my game?
Which motivations are most internal? Which are most external?
Which are pleasure seeking? Which are pain avoiding?
Which motivations support each other?
Which motivations are in conflict?

From Schell (2015, p.153).

Table 2.7: Schell's Lens of Novelty

What is novel about my game?
Does my game have novelties throughout or just at the beginning?
Do I have the right mix of the novel and the familiar?
When the novelty wears off, will players still enjoy my game?

From Schell (2015, p.155).

example of what seems to be commonly held as true: plants seek sunlight to survive; but this contradicts the fact that fungi thrive in the dark.

Alongside game dynamics, which are how game mechanics create a game experience, are other game elements that can have a motivating effect on players. These elements are often associated with the term *gamification*, though they often also feature in fully-fledged games; the distinction here is being made between fully-fledged games—these are largely self-contained environments—and gamified systems, where game elements are a feature embedded in a non-game context. There are contradictions in the literature about whether gamification is under the umbrella of serious games (suggested by Egenfeldt-Nielsen et al. 2016), or something separate (as suggested by Deterding et al. 2011). Deterding et al. do point out that the lines distinguishing a game from an "artifact with game elements" is a "blurry" one.

There is also the argument that games themselves can be gamified (Hamari and Eranti 2011). This suggests that there are elements of games that are separate from the classic notion of game experience. Hamari and Eranti point to the example where there is an imperative, sometimes against game developers' wills, to add an achievement system to a game. This is sometimes done as an afterthought in post-production leading to poorly-designed achievements (also referred to as badges or trophies). When considered against the core game experience, phrases like “secondary reward system”, “stored outside ... individual game sessions”, and “separated from the rest of the game” are used (Hamari and Eranti 2011, citing Montola et al. 2009, Björk 2011 and Jakobsson 2011).

Three of the most common game elements associated with gamification are *badges*, *leaderboards* and *points*. Deterding et al. (2011) point to these (they use the term *level* instead of points, meaning the ability to level up, which could require accumulating points) as examples of game interface design patterns; in other words, things players can easily see.

Badges are optional rewards and goals one step removed from the core activities of a system according to Hamari (2017). The use of the word *optional* needs to be clarified, though: there are badges that can optionally be pursued (for example, find ten hidden objects), but there are other badges that are awarded without negotiation with a user or player. An example is Audible’s mobile application, which awards a “Night Owl” badge for listening for at least eight hours at night; it seems unlikely that many audio-book listeners will pursue that goal, and will instead receive the reward through behaving as they normally would.

Having clear goals, such as those embedded in badges, would seem to suggest that they will intrinsically increase performance, according to Bandura (1993): expectations are elevated, self-efficacy is enhanced, and completing goals (e.g. being awarded badges) increases satisfaction and the likelihood to take part in future activities within the same context.

Past studies on the use of badges have revealed mixed results. Hamari (2017, Table 1) aggregated results from six studies published between 2009 and 2013. One study from an education context showed only positive effects on students, including increased time spent engaging with the system. But other studies revealed issues, such as undesirable changes in behaviour, including focusing too much on the activities that awarded badges to the detriment of those that did not. Another outcome was positive effects on those who diligently monitored their badges, but no effect on those who did not.

da Rocha Seixas et al. (2016) found that gamification positively affected student engagement with a positive correlation to the number of badges awarded. In the significant main study undertaken by Hamari (2017) on the users of a utilitarian trading service (over the course of two years with 1,410 participants), results were positive from four perspectives with very few caveats: badges had a positive effect on productivity, quality of use, social interaction, and general use (e.g. number of page views).

Research has shown that a leaderboard can be a motivator to do better—Landers et al. (2017) found that employees set personal goals at or near the top of a leaderboard. The authors relate this to goal-setting (discussed in Section 2.5.4). However, Hamari et al. (2014) cites research that shows users falling into distinct categories with some wanting to be at the top of the leaderboard and others just content to be on the leaderboard.

2.3.3.4 Narrative

Human beings are storytellers and the making of meaning, including our own identity, is a narrative process (Clark and Rossiter 2008, Foote 2015). Narrative learning is a significant component of transformational and adult learning (Foote 2015). When it comes to educational games, narrative can serve a dual purpose: motivation to learn, for example by stimulating curiosity (as discussed below), and meaning making (that is, cognitive structures in terms of memory and comprehension, e.g. Thorndyke 1977).

It is a rare game that has no story element to it—most people, on the face of it, would probably conclude that the game of chess has no story, being simply a board with pieces and a set of arbitrary rules resulting in an abstract game. However, as Schell (2015) points out, there is a thin storyline of two warring factions that are obviously medieval given the presence of castles, horses and knights. The setting is a battlefield represented by a board with sixty-four squares and the characters, though shallow, are there in numbers (the thirty-two chess pieces).

Malone (1981) writes that fantasy is an intrinsic motivator in a game. Fantasy is an important component in the role of narrative in DGBL (Dickey 2011). Plausibility, which is at the intersection of story and environmental affordances, is also an important component according to Dickey when he writes that “[a game] narrative provides a cognitive framework for problem solving by establishing what is plausible for constructing causal relationships.” This is because, he continues, curiosity is initiated by plausibility and curiosity is an essential component in the motivation to explore. Learners learn better when they actively explore a learning environment (Adams et al. 2012). Narrative, when combined with a game's mechanics and context, can also make the experience of playing a game meaningful (Elson et al. 2014).

When it comes to structuring narratives, Ryan (1991) provides nine different ways the player could advance through the narrative to create a unique story. This includes the network structure that is often used in cave-based adventures, the tree structure that might be used in interactive fiction, the vector with side branches that might be used in a linear story with side quests, and so on. The point is that a narrative structure can be chosen that allows the gameplay and the story to evolve in a linear (like a string of pearls (Schell 2015, p.298-9)) or non-linear way, allowing backtracking, optional quests and so on.

Schell (2015) argues that interactive storytelling (as games allow), while more difficult to implement, are not fundamentally different than traditional storytelling. He argues that while some critics argue that video games do not count as interactive stories because of the lack of an author—or a narrator retelling a story to a narratee (Dubbelman 2016)—players do not care about that if they experience what they consider a story. Perhaps one could argue that the authorship of a game's story is a joint enterprise between game developer and player—the game developer puts the narrative blocks in place along with an allowed structure and the player through agency shapes the story (Rigby and Ryan 2011). Schell (2015) also writes about the degree of freedom a player experiences, which separates games from other media, but also writes about indirect control, which is the degree to which game designers shape the actions of the player. The balance must be struck between a high degree of freedom felt by the player and the indirect control placed on them by the designer.

Two of the most influential books on archetypical story structures are Joseph Campbell's *The Hero with a Thousand Faces* (2008), which recounts classical and recurring story structures from mythology and religion, and Christopher Vogler's *The Writer's Journey* (2007). Both write about the hero's journey, which is constructed from familiar tropes, such as the call to adventure, the mentor, the ordeal, the reward, and so on. It is a familiar structure that has been around for thousands of years, from Odysseus to Christ to Luke Skywalker to Neo (in *The Matrix*).

According to Dubbelman (2016), "mechanics and rules influence (but not determine) the actions of players, and this, in turn, influences what kind of story events can unfold”. However, bringing narrative into DGBL, like bringing learning, requires some thought. A number of researchers have theorised about how to embed the mechanics of narrative into learning games. A Narrative Serious Game Mechanic (NSGM) (Lim et al. 2014) is comprised of an experience (pre, during and post), process, narrative element, a description and an impact (described in Table 2.8). The authors consider NSGM another conceptual / structural layer with NSGMs mapped to game mechanics, similar to the approach of the authors of the LM-GM model discussed in Section 2.3.4.3 (there is a significant overlap in authorship between NSGM and LM-GM).

Table 2.8: Narrative Serious Game Mechanics

NSGM Experience	*Pre, during and post:* event directly involving player interaction with the SG, or sequence where the player is not engaged in active gamelike interaction with the SG, i.e., sequence of tasks / activities related to the NSGM occurrence.
NSGM Process	*Process Step:* Chronology of activities /tasks related to the NSGM. Describes what comprises this step and its various elements.
Narrative Element	*Structure:* Describes the mechanics of activity or information communicated to the player (information element, invitation to act, feedback, information communication, etc.)
Description	Describes the actions of the player or the game in this phase of the process.
Impact	Describes the impact of the step on both the SG experience and the learning outcome both directly and indirectly

2.3.4 GBL Analysis and Design Models

This section presents three of the most widely used models for the development of DGBL solutions. There is an ever-increasing amount of literature stating that instruction design methods and theories need to be embedded in the development of DGBL (Van Staalduinen and de Freitas 2011). The AMDGBL is not prescriptive about the choice of models, lenses or frameworks for the formative and summative evaluation of a serious game, so serious game designers might choose alternatives, including ones yet to be published. Other models are touched on in other sections of this thesis, for example the experiential gaming model in Section 2.5.5.6 that embeds experiential learning and flow into the model.

When constructing a DGBL model or framework, Van Staalduinen and de Freitas (2011) suggests asking four questions provided by Anderson and Krathwohl (2001) to ask about intentional learning outcomes (Van Staalduinen and de Freitas come from the perspective that DGBL is designed for a specific purpose, so while informal learning can take place, the focus is on intended learning):

1. *The learning question.* What should the learner learn?
2. *The instruction question.* How should instruction be delivered in order to provide high levels of learning?
3. *The assessment question.* How should accurate assessment instruments be designed or selected?
4. *The alignment question.* How should learning, instruction, and assessment be balanced with one another?

The answers Van Staalduinen and de Freitas (2011) provides results in a framework for DGBL that is also worth considering when analysing a DGBL solution.

2.3.4.1 The Four Dimensions Framework (4DF)

The four dimensions framework (4DF) for game-based learning and simulations (de Freitas and Oliver 2006) offers four dimensions, and questions to ask within them, as a checklist for the evaluation of the use of educational games and simulations under the headings of *Context*, *Learner Specification*, *Pedagogic Considerations* and *Mode of Representation*.

This is similar to traditional approaches to instructional design, such as the analysis phase of the ADDIE model (discussed in section 2.5.5.8), which begins with a needs analysis of the intended audience, learning constraints, delivery options, pedagogical considerations, and so on.

An example of the 4DF framework in action is provided (a learning game called *MediaStage*). Under *context*, the authors list facts such as the context being school-based in classrooms and that the tool will support the GCSE-level Media Studies subject. The *learner specification* includes student age, the fact that it is not limited to GSCE level, can be used individually or in groups, and caters for different learning styles. The *pedagogic considerations* include Kolb's experiential learning cycle, the game's learning outcomes and activities, the use of a debrief for reflection and how the game will be embedded into lesson plans. The *mode of representation* (or tools for use) includes fidelity through 3D animated characters and interactivity. Another example of the framework being employed is Lorenzo et al. (2012), which used the 4DF to evaluate the effectiveness of massively-multiplayer online learning platforms (MMOLs).

While the model can be used to evaluate DGBL to determine the types of learning that will take place and broadly what medium will be used, what the model lacks, however, is an expansion of the *mode of representation* dimension to include a model or framework for how the learning described under the *pedagogic considerations* dimension is to be implemented using the mechanics of a game. The limitation (lack of practical application) is noted in (Van Staalduinen and de Freitas 2011) and is addressed somewhat by the following two models.

2.3.4.2 The Game Object Model (GOM) Version 2

The Game Object Model (GOM) version II theoretical framework (Amory 2007) uses the object-oriented programming metaphor to describe the abstract and concrete interfaces between learning objects and game objects. The model describes a number of interfaces to game elements that can be abstract (pedagogical and theoretical constructs, such as critical thinking, emotiveness, goal formation and goal completion) or concrete (design elements, such as story, plot, backstory, graphics and sound). These are then mapped to the intended learning outcomes and the game mechanics.

The model is intended to "facilitate the understanding of complex situations" (Amory 2007). It does this through concepts such as *spaces* and *core concepts*. The spaces include the game space, which itself consists of a visualizations space, which consists of elements and problems spaces. There is a social space, which is separate from the game space, but both share (inherit from) the problem space. The core concepts are *game defintion*, *authentic learning*, *narrative*, *gender*, *social collaboration* and *challenges-puzzles-quests*.

Amory uses the case study of a game called yKhozi to illustrate how the model can be used. For example, under the core concept of *authentic learning*, five interfaces are listed:

- Authentic (concrete)
- Multiple views (concrete)
- Transformational (concrete)
- Relevance (abstract)
- Model-building (abstract)

Amory (2007) describes how these interfaces were implemented as follows:

> The game takes place in an African village where the player learns about a number of game characters including a doctor and nurse and about important African diseases. The player faces a number of authentic interrelated puzzles of which some are based on medical and scientific procedures (such as using a microscope or preparing a poster for information distribution) that require an understanding of HIV/AIDS, malaria, tuberculosis and cancer. It is suggested that during gameplay participants are encouraged to solve the puzzles collaboratively.

While the model tries to help DGBL designers to represent "complex situations", this may be to the model's detriment. In a study conducted by the authors of the LM-GM model (discussed in the next section), the less technical the expertise of the participants, the less usable they found GOM in comparison to LM-GM, which takes a less prescriptive approach to how games are structured and instead focuses on the learning mechanics and how they map to game mechanics. Arnab et al. (2015) also criticize the GOM model for how it "does not sufficiently support a description of an SG's learning aspects/goals and their relationships with game components." An additional criticism of GOM is that it does not take gameplay and flow into account (Kiili 2005).

2.3.4.3 The Learning Mechanics-Game Mechanics Model

A number of models have attempted to map the mechanics of learning to the mechanics of games. These mappings have been called *serious game mechanics*

(SGM) by Suttie et al. (2014) and Arnab et al. (2015). Suttie et al. (2014) presents a *Game Mechanics Learning Mechanics* framework, which maps learning and game mechanics to Bloom's taxonomy, specifically from lower to higher order thinking skills. The authors note that while there are several catalogues of game mechanics and genre, such as the one provided by Sicart (2008), there were none for what they called serious game mechanics.

Arnab et al. (2015) build on this framework, producing a model that is a more practical tool for serious game analysis and design. SGMs, the authors write, "reflect the complex relationships between pedagogy, learning and entertainment/fun, joining educational and gaming agendas." The intention of the model, when designing serious games, is to select the types of learning to be embedded in the game and choose appropriate game mechanics to facilitate the type of learning. The model features 31 learning mechanics, which are mapped to 38 game mechanics.

Arnab et al. (2015) performed a study with serious games practitioners and found that the LM-GM model was more usable (according to the System Usability Scale) than the GOM model, particularly when the participants were less expert in the design of games.

An example of the model in action is the InTouch project (Imbellone et al. 2015). The project developed 30 mobile games as part of an ad hoc kit for adult learners. The developers used the LM-GM model to decide how five different types of interaction (branching story, interactive map, multiple choice, quiz and simulation) would be implemented through game mechanics. For example, for *interactive map*, the game mechanics of goods/information, role play, selecting/collecting, questions and answers, and feedback were selected.

To illustrate graphically how the model can be applied, taking inspiration from the *Re-Mission* case study presented in Arnab et al. (2015), Figures 2.3 and 2.4 show how a game design (the structure of which is in Figure 2.3) can be mapped to the learning mechanics and game mechanics listed in the LM-GM model (Figure 2.4). The model is from early in the research for this thesis and was developed into a point-and-click 3D adventure game prototype. Development of the prototype stopped in 2016 and focus shifted to the graph game. At the beginning of each level in the game, there is a briefing from the main protagonist's editor who explains the tasks to complete. In terms of learning mechanic, it is *instructional*, and it can be implemented through the game mechanics of *cut scenes/story* (to have the editor say what the goals for the level are) and *levels*, because each level in the game begins with such a briefing. As part of the game, the main protagonist (an investigative journalist) has to "write" and "file" an article (constructed from items discovered during the level, including dialogue from other non-player characters); this involves the learning mechanics of *analyse*, *ownership*, *accountability* and *responsibility* implemented through the game mechanics of *design/editing* and *ownership*—these are at the upper end (higher-order thinking) of Bloom's taxonomy, which the model is also mapped to.

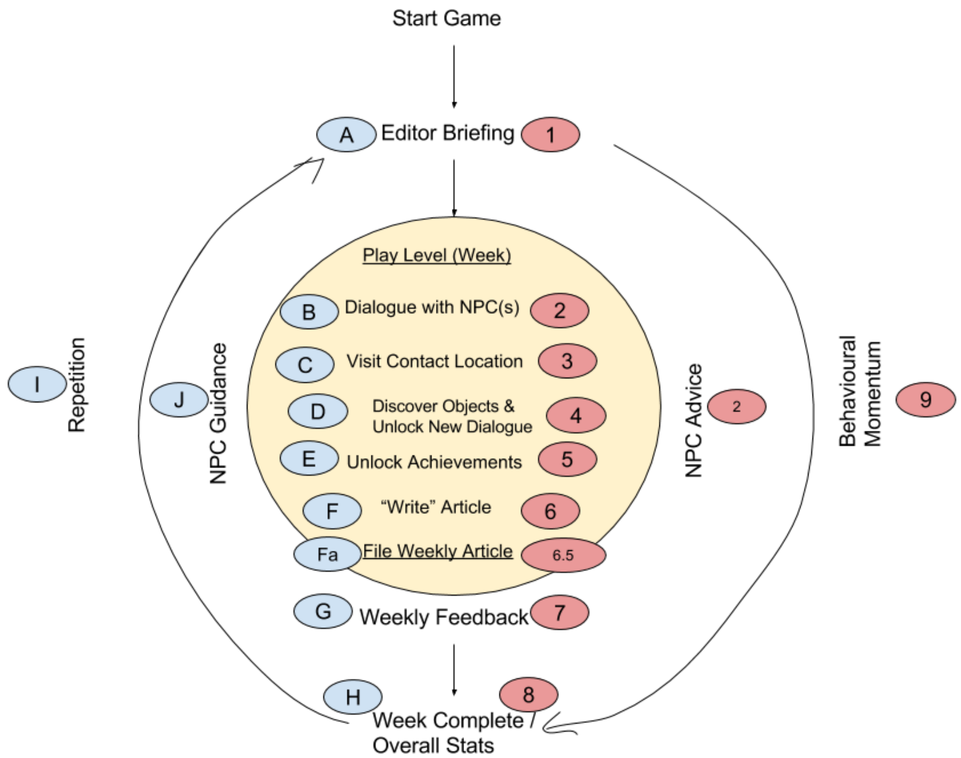


Figure 2.3: Structure of initial prototype game mapped to LM-GM.

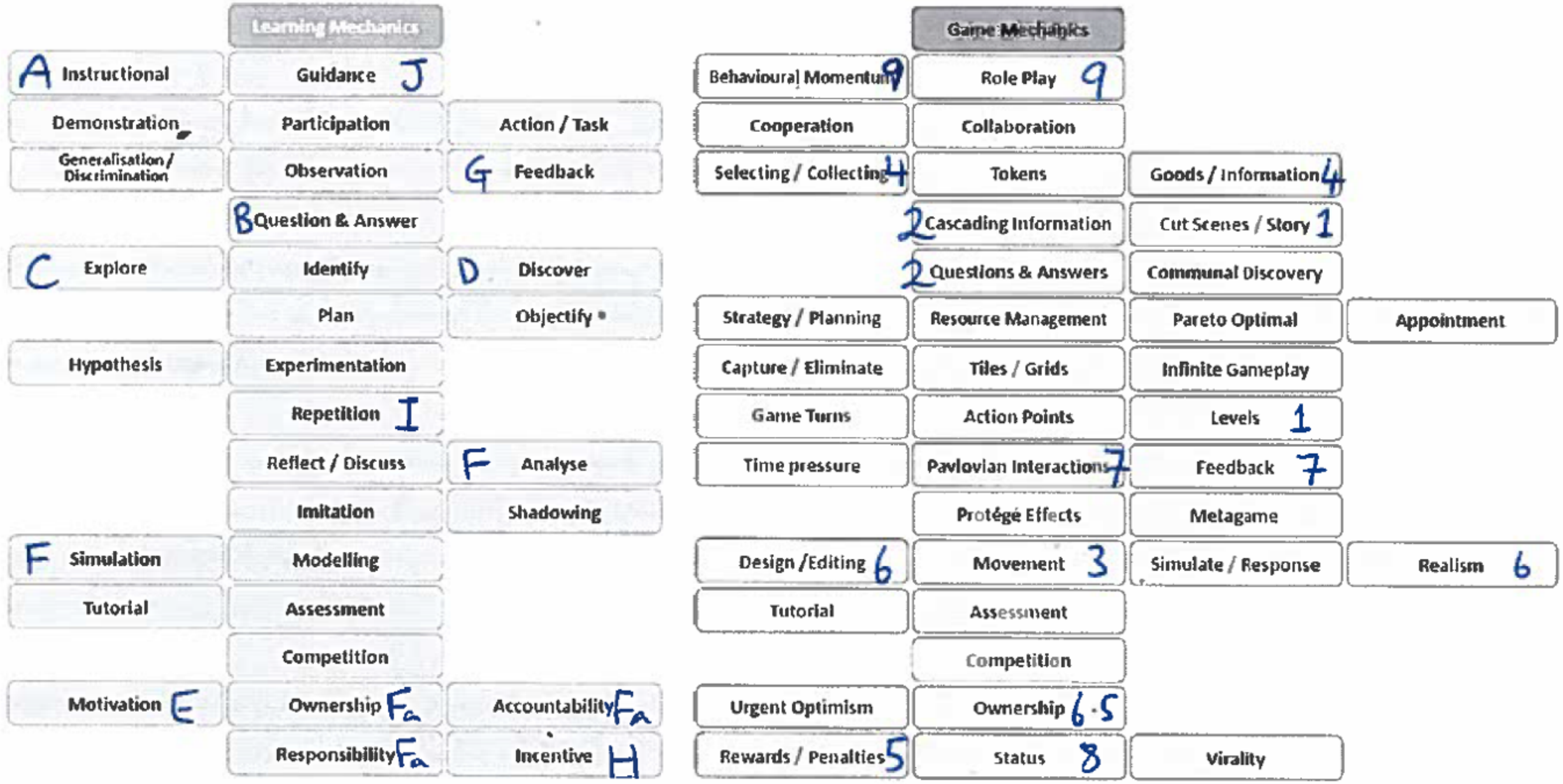


Figure 2.4: Cross referencing the Learning Mechanics and Game Mechanics with the game structure.

It should be noted that the element of narrative can be an additional conceptual layer and this was discussed in Section 2.3.3.4 in relation to NSGMs (see the mapping of LM, GM and NM in Lim et al. 2014, Fig. 1 for an example).

2.3.5 Recent Examples of DGBL

This section discusses four very recent examples of DGBL solutions that appear to be innovative or employing best practice in DGBL. The examples are intended to give a sense of the wide variety of games, ranging from kinaesthetic learning with VR, to learning to program machine learning, to learning about challenging topics such as depression and cancer, but also a sense of what very recent games (published since 2017) are attempting to achieve.

Words in Motion (Vázquez et al. 2018) by researchers in MIT's Media Lab is the embodiment of learning by doing or, to put it another way, an example of kinaesthetic learning (this is discussed in Section 2.4.2.1). Learners use VR to engage in activities, such as cooking, while words in a new language are presented to them. Figure 2.5 shows a player using the HTC Vive HMD and controllers to grab a salt cellar, triggering the word *sprinkle* as the player begins shaking the salt cellar. A study of 57 participants showed that while there was little difference in short term gains versus text-only learning, there was a significantly higher retention rate over the long term.

In *while True: learn()* (Luden.io 2017), an inexperienced software developer works on programming jobs (in particular, machine learning) to feed himself and his cat (see Figure 2.6). The game uses visual programming (similar to Blueprint, which is discussed in Section 4.4.4.1) and the player can add program nodes and connect them.

Other recent games tackle difficult subject matter to help demystify them or equip people with correct terminology. *Please Knock on My Door* (Levall Games 2017) is a story-driven serious game about depression and anxiety. *AlphaBeat Cancer* (Beaba 2017) is a set of mobile-based mini-games that teaches children about some of the terminology related to cancer. See Figure 2.7 for screenshots of both. *Please Knock on My Door* can be considered a persuasive game with a procedural rhetoric (as per Bogost 2007)—the real issues that affect people with depression and anxiety are played through in the game.

Figure 2.5: A screenshot from a gameplay video of *Words in Motion*; included with permission.

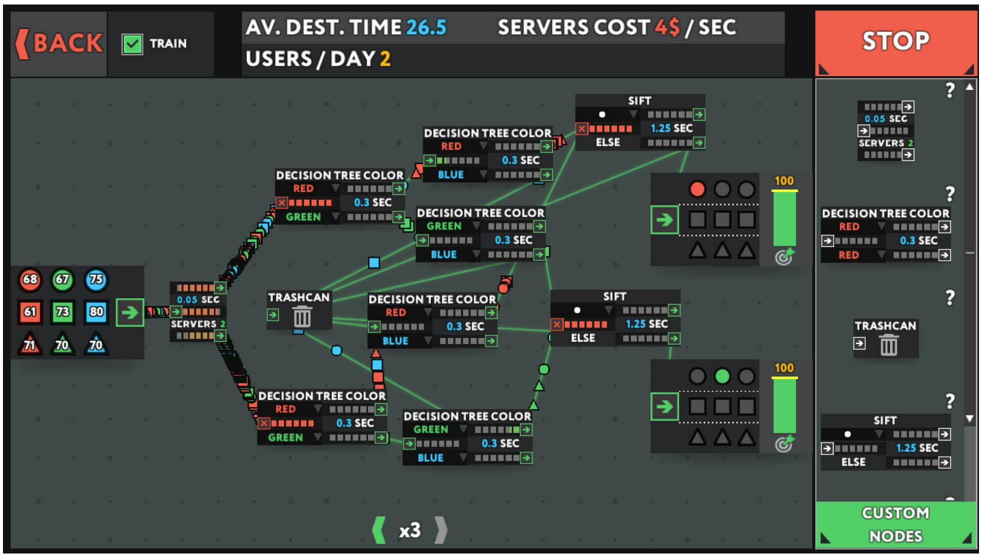


Figure 2.6: A screenshot from *while True: learn()*; included with permission.

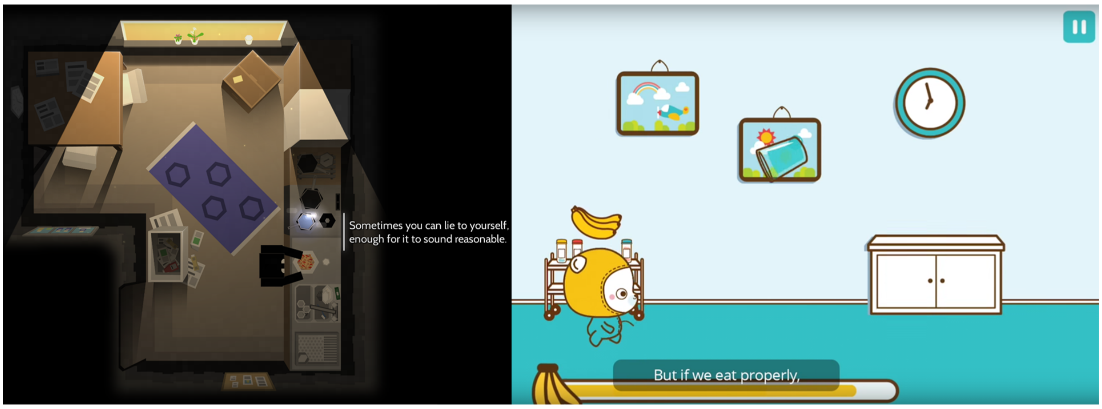


Figure 2.7: *Please Knock on My Door* (left) and *AlphaBeat Cancer* (right).

2.3.6 Video Games and Diversity

An increasingly important factor in the design of video games, and by extension games for learning, is how inclusive they are. Video games have been seen as largely the preserve of the male gamer. However, several studies have shown that a significant minority of game players are female, though they tend to play for shorter amounts of time than males (Greenberg et al. 2010, Dindar 2018). Females also prefer different genres of game. All of these factors should be taken into consideration when designing and delivering game-based learning.

According to a study by Greenberg et al. (2010), younger players (at primary school level, for example) preferred fantasy, whereas older players in the study (at undergraduate level) preferred competition. The same study found that males had a preference for physical games, whereas females preferred more traditional, thoughtful games. Dindar (2018), citing Elliot er al. and Rehbein et al., writes that males prefer shooter, strategy and role playing games, whereas females prefer brain games, such as board, puzzle or skill games.

The effects that games can have on players can also be effected by gender. For example, Feng et al. (2007) suggest that by playing action games for a number of hours, women benefit more than men in terms of higher-level spatial cognition (such as mental rotation), something that benefits practitioners in the mathematical and engineering sciences, where men have tended to dominate—the study suggests that the gap in spatial skills between men and women is dramatically reduced.

Males have more experience and skill in playing video games (Dindar 2018), and so this factor should be taken into account when looking at the context and profile of the learners. This suggests that to be fair to female learners, more time or certain allowances should be made to ensure that female learners are given time to adapt to the playing of video games.

Other diversity factors, such as age, race and sexuality, are important factors. Role models can be important for learners, either positive or negative (Lockwood et al. 2002). Video games have not tended to feature gay, lesbian, bisexual or transgender role models (Shaw 2009). Stereotypes have tended to abound in video games also. Malkowski and Russworm (2017) provide numerous example of games that include negative stereotypes, such as nerds, the femme fatale and the portrayal of black people. It should be noted that there are exceptions. For example, the game *The Last of Us* (Naughty Dog 2013), in its add-on chapter, *Left Behind*, shows one of the main characters, a teenage girl named Ellie, in a coming-of-age moment as she kisses her female friend. The moment is depicted tenderly and arguably creates a positive LGBTQ character.

2.4 Virtual Reality

2.4.1 Background

While it was in 1968 that Ivan Sutherland created the first virtual reality (VR) system as we now understand them, with computer graphics and a head mounted display (HMD) (Pausch et al. 1997), there have been many previous attempts at providing immersive experiences that approached a virtual reality. In 1830, Charles Wheatstone created the “reflecting mirror stereoscope”, which had “two centred mirrors at 45 degrees to each eye and reflecting right- and left-eye images”, thus creating a 3D cinematic effect (Zone 2014, p.5). This was taken a step further by others attempting to bring the viewer inside the experience, such as Morton Heilig and his Telepshere Mask, patented in 1960, and the Sensorama device, which he patented in 1962 (Ewalt 2018, p.42-44). The Telesphere Mask is regarded as the forerunner to the modern HMD. The Sensorama used binocular lenses through which the user watched a 3D movie with stereo sound, as well as having air blown at them and various scents released, as the user was moved about on a motorcycle ride through an immersive environment.

An alternative to the HMD is the CAVE, which is a multi-wall projection system designed primarily for visualization (Cruz-Neira et al. 1993). An advantage is that multiple people can share the same CAVE space, something that would require multiple networked PCs if HMDs are used. However, disadvantages include cost and portability. What seems like a viable alternative to a CAVE-like system is augmented reality, which can allow multiple people have a shared virtual experience without disembodiment from the real world, allowing the user to work with traditional tools alongside virtual objects (Billinghurst et al. 1998).

A sense of presence is discussed in the next sub-section and there are several peripheral devices for additional sensory input or haptic feedback. The Sensorama device assaulted the senses with wind, smell and vertical and lateral movement. Hand-held controllers, such as the Oculus touch controllers, provide simple haptic feedback (rumbling). A number of companies are moving towards full-body haptics, though the majority of solutions are based currently on gloves (such as HaptX[5] and VRgluv[6]).

Another approach is full hand tracking where fine-grained motor activity in the hands can be tracked in VR environments. The existing controllers that ship with Oculus Rift and Vive HMDs allow for basic hand tracking. The sensors embedded in the controllers can detect fairly accurately when a thumb is raised or a forefinger is extended to a point. Full hand tracking is at the level of each finger joint to potentially track a wide range of gestures, such as pinching to contract and expand, or zoom and pan out. An example is Leap Motion[7].

2.4.2 VR and Learning

There are a number of features inherent in VR that lend them to learning. Bricken (1990) went as far, early in the research on VR and learning, as to state that the “characteristics of VR are the same as those of good teaching”, where a programmable environment (analogous to curricula) is created for a student to participate in, echoing the writings of John Dewey who believed that children thrive on experience and interaction with the school curriculum.

Much research in VR and learning has centred on the concept of *presence* (Mikropoulos and Natsis 2011). Witmer and Singer (1998) define presence as:

> the subjective experience of being in one place or environment, even when one is physically situated in another.

Witmer and Singer further explain presence as an awareness phenomenon created by a mix of the external (stimulation of the senses, environmental factors with certain affordances) and internal (tendency to become involved on the part of the user). Several factors, Witmer and Singer explain, can affect the level of presence experienced by individuals, but focus is an important factor, with a coherent environment that enables rather than forces

[5] http://haptx.com
[6] http://vrgluv.com/
[7] http://www.leapmotion.com/

involvement being key. Involvement as well as *immersion* are necessary to experience presence, they further explain. They define immersion as:

> a psychological state characterized by perceiving oneself to be enveloped by, included in, and interacting with an environment that provides a continuous stream of stimuli and experiences.

Witmer and Singer (1998, Table 1) provide a grid of hypothesized factors that can improve presence, which is reproduced in Table 2.9

Table 2.9: Factors Hypothesized to Contribute to a Sense of Presence

Control Factors	Sensory Factors	Distraction Factors	Realism Factors
Degree of control	Sensory modality	Isolation	Scene realism
Immediacy of control	Environmental richness	Selective attention	Information consistent with objective world
Anticipation of events	Multimodal presentation	Interface awareness	Meaningfulness of experience
Mode of control	Consistency of multimodal information		Separation anxiety/ disorientation
Physical environment modifiability	Degree of movement perception		
	Active search		

Mikropoulos and Natsis (2011) provide a list of VR characteristics that contribute to learning:

- First-order experiences
- Natural semantics
- Size
- Transduction
- Reification
- Autonomy
- Presence

There are significant overlaps between Table 2.9 and the above list. First-order experiences (such as first-person perspective and being able to see virtual hands) are linked to factors such as sensory modality and multimodal presentation. Autonomy is linked to factors such as degree of movement perception and the ability to modify the physical environment. Transduction (in the sense of transporting stimuli to the central nervous system) and reification (making the abstract real) are related to factors such as environmental richness and multimodal presentation. Both reification and natural semantics (the ability to represent without resorting to symbols, such as avoiding the use of sticks and balls to represent atoms) are related to the realism factors.

Size is a VR characteristic worth expanding on. Learners can navigate virtual worlds in first-person perspective at the micro and macro levels—for example, interacting with atoms (Kontogeorgiou et al. 2008) or experimenting with Newtonian mechanics in *Universe Sandbox 2 VR* (Giant Army 2016). In this case, it is the player avatar (whether visible or not) that is resized to fit this new world.

Pausch et al. (1997) demonstrated that there can be a quantifiable difference between being immersed in VR and using stationary computer monitors. While VR participants did not find targets (letters among many letters on the floor, ceiling and walls of a virtual room) significantly faster than participants using a monitor, there was a statistically significant difference when participants were asked to confirm that a target did not exist, with VR participants significantly faster at doing so. The authors claim that this is the result of the immersion of VR—a previous study they carried out had found that uncamouflaged targets (red letters among black letters) were significantly faster to find using VR, but the authors suggest this was because of the speed of camera movement in VR.

It seems intuitive that an immersive VR environment that allows interaction with 3D objects would benefit learners from an active learning perspective. James (2002) found that when a comparison was made between those users who were able to interact (for example rotate) a 3D object versus merely observing the object, there was a statistically significant difference in the amount of time it took for users to later recognise the same object. This is consistent with the view of constructivism, discussed in Section 2.5.1.4, that learners construct meaningful knowledge from individual experiences and that the emphasis is on the design of learning environments rather than a fixed sequence of instructions. VR offers the educator the opportunity to design learning environments that foster many of the features of learner-centred education, such as real-world, authentic experiences.

2.4.2.1 Bodily Movement, Learning and VR

The concept of kinaesthetic learning was proposed by Howard Gardner in his book *Frame of Mind: The Theory of Multiple Intelligences* (1983). Specifically, he referred to it as *bodily-kinaesthetic* learning, defined as “[a]n ability to use one’s own body to create products or solve problems”. It was, in fact, one of eight types of intelligence he proposed. Each intelligence, to earn the right to be considered a separate type of intelligence, must demonstrate certain characteristics, such as having “some basis in evolutionary biology”, having “a distinct neural representation”, and a “distinct developmental trajectory” (Davis et al. 2011).

Reid (1987) makes a distinction between kinaesthetic learning, which he describes as being totally physical, and tactile learning, which is hands-on, such as with model building (and is therefore only mildly physical). Both are distinct from learning involving no physical engagement, such as visual or auditory learning. Another example of a moderately physical approach to learning is gesture-based learning. An example is the use of the Microsoft Kinect to track mouth, arm and leg movements, as was the case with a study by Chao et al. (2013), which showed improved recall for learners who used gestures compared to those who used a mouse.

There is a positive link between exercise and the size of the brain’s hippocampus, where learning and memory systems reside, as well as improved focus (McGlynn and Kozlowski 2017). Mobley and Fisher (2014) argue for the application of kinaesthetic learning in college classrooms and provide a table of example kinaesthetic activities, which involve students being active, such as tossing a survey around a room or having students line themselves up like a Likert scale—they also list some limitations, primarily to do with space limitations, but these seem largely solvable with the use of VR.

The support of the graph game for physical as well as virtual locomotion and physical arm and hand movements, is therefore arguably building on and leveraging a different type of intelligence than reading or using pen and paper. Active learning need not necessarily be physical in nature, but the graph game is an example of active learning that is physical. Whether the graph game is kinaesthetic or tactile is open for argument—Davis et al. (2011) give the examples of ballet (very physical) and orthopaedic surgery (mildly physical) as examples of high bodily-kinaesthetic intelligence, whereas Reid (1987) would likely consider ballet as kinaesthetic and orthopaedic surgery as tactile.

The applicability of kinaesthetic learning to VR appears to be clear. In Section 2.3.5, the example of VR-based kinaesthetic language learning at MIT was discussed. However, the field of learning styles (of which kinaesthetic learning is but one) is a contested one with a "myriad of tests; contested, confused and overlapping definitions and terminology; inappropriate measurement and lack of independent evaluation ... lack of theory and its isolation from main stream psychology and cognitive science" (Peterson et al. 2009, summarising many authorative sources). This is why the term *preference* is used in this thesis rather than *style* and it becomes less about labelling learners with a style and more about listening to learners expressing preferences and responding to them (see Section 2.5.2 for more on learning preferences, including criticism; see Sections 5.3.3 and 5.3.4 for findings and discussion of findings from the learner study, including preferences expressed by some study participants for visual or hands-on learning).

A related research area is psychomotor skills, which are voluntary limb, joint and muscle movements in response to stimuli in the brain (Nicholls et al. 2014). Psychomotor skills can be open or closed, with closed meaning those tasks that are carried out without variation, such as when we wash hands, whereas open means the tasks have some degree of variation.

Simpson (1971) wrote that many practitioners bemoaned the lack of a psychomotor domain in the leading taxonomies of the time, such as Bloom's. Kratwohl et al. (1964), though, had defined psychomotor objectives as those that "emphasize some muscular or motor skill, some manipulation of material and objects, or some act which requires a neuromuscular coordination." Simpson went on to define a complementary psychomotor domain which progressed from perception (awareness of need to act) to origination (creating new acts) (Driscoll 2005, Table 10.3).

2.4.3 VR Motion Sickness

Given that there is a significant difference between what consumers choose to do freely with VR in their own homes and what education institutions do with

VR with large numbers of students, it is worth exploring the negative impacts of VR. This is important from a universal design for learning perspective, which is covered in Section 2.7. For example, it would not be sensible to design a VR learning environment that makes the majority, or even a significant minority, of learners feel nauseated.

Pausch et al. (1997) reported that while they were able to complete their study with 48 participants, there were an additional 3 participants who could not complete the study due to feeling slightly nauseated; each of the 3 reported that they were prone to motion sickness.

HMDs, and other contemporary technologies, differ from vehicles in that there is no intertial displacement and so when there is nausea associated with these technologies, it is a visually-induced motion sickness (VIMS) (Kennedy et al. 2010). There is a significant gender difference with motion sickness—a ratio of 5:3 (women to men) exists with seasickness (Lawther and Griffin 1988), for example. A study of 18 men and 18 women featuring two experiments showed that women experienced motion sickness significantly more often than men, though the severity of symptoms was similar (Munafo et al. 2017).

The Oculus Home application is a portal where VR games can be purchased and the user's library of existing games can be accessed. When browsing games in their online store, a comfort rating can be viewed. Oculus claim to work closely with developers to assign the correct rating[8]. Games (or experiences) with a *Comfortable* rating are suitable for most people and "generally avoid camera movement, player motion, or disorienting content and effects". *Moderate* comfort is described as being appropriate for most, but not everyone. This is quite vague as the word *appropriate* could entail some minor discomfort that many might be unable to bear for long. The final rating of *Intense* is described as being unsuitable for most people, often involving significant camera or player movement.

To get a sense of what VR motion sickness is like, this researcher trialled several games with varying degrees of comfort rating. Though VR motion sickness is very much dependent on the individual, it seems reasonable that any developer of VR experiences should try to get a personal sense for the limits of the technology with respect to player movement, camera use and other effects that might induce motion sickness.

[8]See https://support.oculus.com/1639053389725739/ for this claim and a list of comfort ratings.

A perusal through the Oculus online store shows that the great majority of VR experiences are rated as comfortable. They almost always use a teleportation mechanic if player locomotion is required. An example is *Robo Recall* (Epic Games 2017), which is provided for free with the Oculus Rift. Locomotion is by teleportation with a blue arc and arrow used to show the player where they will teleport to and the direction they will be facing (see Figure 2.8).

Figure 2.8: Teleportation mechanic in Robo Recall.

Two games with a moderate comfort rating are discussed because they show two ways in which free movement is allowed. The first is *Lone Echo* (Ready At Dawn Studios 2017), which is a first-person perspective game set in zero gravity. Two factors avoid an intense comfort rating: zero gravity means the player never has the sense that a fall is imminent (reducing the sense of vertigo) and though there is free movement, it is in a straight line. In addition, a full avatar is provided: hands are always visible and looking down shows a torso and legs, giving an increased sense of immersion.

The other moderate comfort game discussed is *Lucky's Tale* (Playful 2016), which is a third-person platformer with a table top perspective. The player avatar moves freely within the player's viewport, which in itself does not cause discomfort, however the player must move freely to follow the avatar, which can induce a mild sensation of motion sickness.

Figure 2.9: Third-person perspective in Lucky's Tale.

The final game discussed here is *DiRT Rally* (Codemasters 2016), which has an intense comfort rating. Though the player is in a fixed seated position, which normally mitigates the sense of motion sickness, the player experiences every bump and jump of a rally event (see Figure 2.10).

The Oculus store includes the ratings and comments of people who played the game. For each of the games discussed above, three months of comments were examined (up to 9th August 2018) for issues related to motion sickness, with the exception of *DiRT Rally*, which had a smaller number of comments and a lot of them related to technical issues related to installation necessitating that comments from further back be examined. Tables 2.10 and 2.11 give an idea about the varying degrees of discomfort experienced by players. There were no reports of motion sickness, nausea or dizziness in the comments related to *Robo Recall*. There were very few such discomforts reported for *Lone Echo*.

Figure 2.10: Behind the wheel in DiRT Rally.

Lucky's Tale did have a more significant number of reports of discomfort, tending to be mild to moderate. *DiRT Rally*, though, did feature reports of more serious discomfort, including severe nausea.

Table 2.10: Analysis of player comments related to 4 VR games

VR Game	Comfort Rating	Comments	Mild discomfort	Severe discomfort
Robo Recall	Comfortable	65	0	0
Lone Echo	Moderate	78	1	1
Lucky's Tale	Moderate	23	4	3
DiRT Rally	Intense	40	1	3

While this does not represent a comprehensive study, it points to certain mechanics as lending themselves more to a comfortable experience, which is something desirable in an educational setting where it is okay to entertain learners, but not to thrill them to the point of vomiting. The teleport locomotion mechanic of *Robo Recall* appears to be universally comfortable. The zero gravity, straight line locomotion of *Lone Echo* also appears to be quite comfortable despite its *moderate* comfort rating. The approaches of *Lucky's Tale* (free movement over an environment while controlling a third-person perspective avatar) and DiRT Rally (significant lateral and vertical movement in first-person perspective) appear to be too uncomfortable for consideration

Table 2.11: Example comments on VR discomfort

VR Game	Comments (with original spelling errors)
Lone Echo	... ive never been one to get easily queasy, but the moving system in this drifiting through space just gets me the right way where i just simply cant enjoy this game ... i just cant get past the nausea.
Lone Echo	You might feel a bit nauseous at first but you quickly get used to it.
Lucky's Tale	... every time the camera moved I ended up feeling incredibly motion sick and dizzy
Lucky's Tale	Some people get dizzy because of the moving camera but I got quickly used to that and have not problems now.
Lucky's Tale	I cannot play this for more than 2 minutes without becoming dizzy and sick to my stomach.
Lucky's Tale	... the camera is so irritating, sometimes it even get's me dizzy.
Lucky's Tale	Its a fun game with a good story but if u play like 20-30 minutes u already get nauseous because of the camera going up and down rotating and moving how it wants
DiRT Rally	Don't play it in VR unless u want sick
DiRT Rally	The first Game ever that make me feel like i need to puke urgend. But i dont know why. Never had any nausea problem since i have a rift.
DiRT Rally	Crashing gives me serious motion sickness

in an educational setting.

This is largely consistent with research that shows that VR motion sickness differs from game to game. Merhi et al. (2007) found that there was a significant difference between seated and standing VR experiences, with seated positions lending themselves to a reduction in motion sickness. Munafo et al. (2017) found a significant difference between two experiments designed to induce symptoms of motion sickness using the same technology (Oculus Rift), suggesting that it is content more so than platform that is a factor in incidence of motion sickness.

When considering that content is the biggest factor in VR motion sickness (or VIMS), there are several components of the content that contribute to motion sickness. Background patterns are a factor, as shown by Kennedy et al. (2002) where wallpaper patterns induced different levels of VIMS. Other factors include the locomotion mechanic and whether the player is seated or standing.

That conclusion by Merhi et al. (2007) is interesting when compared to the finding from the quick analysis of four VR games in this section: that the game that induced the worst level of discomfort was a seated game, *DiRT Rally*. This highlights that there is no typical player position or genre of game that guarantees a reduction in discomfort. While seated games might in general reduce motion sickness, flinging players around sharp bends or jumping over crests in a rally car will still bring some players to the point of vomiting.

2.5 Teaching and Learning

2.5.1 Theoretical Perspectives on Education

There are currently three main theoretical perspectives on the theories of learning: behaviourism, cognitivism and constructivism (Yilmaz 2011). While these are explored in the following subsections, this section begins with their historical underpinnings and follows them with an example of an emerging theory of learning influenced by advances in technology, connectivism.

It is advantageous as a designer of learning tools and content to be familiar with all branches of educational theory and to select those aspects that suit the situational or contextual constraints of what is being taught and the particular learning and teaching styles or preferences of the learners and teachers, respectively. It is not only useful to be able to distinguish among theories of learning, but it is also important to understand them as an educator (Yilmaz 2011) and the commonalities of them as diverse as they are. Schunk (2012) provides five learning principles that are common to the majority of theories of learning:

- Learners progress through stages/phases
- Material should be organized and presented in small steps
- Learners require practice, feedback, and review
- Social models facilitate learning and motivation
- Motivational and contextual factors influence learning

Schunk also has six questions to ask when investigating a learning theory:

- How does learning occur?
- What is the role of memory?
- What is the role of motivation?
- How does transfer occur?
- Which processes are involved in self-regulation?
- What are the implications for instruction?

The sixth question concerning instruction is an addition to Schunk's list of questions from prior editions of *Learning Theories: An Educational Perspective*. The prior list, which did not mention instruction, was added to by Ertmer and Newby (1993) as follows:

- What basic assumptions/principles of this theory are relevant to instructional design?
- How should instruction be structured to facilitate learning?

Schunk's sixth question encompasses both of those questions, but Ertmer and Newby's questions focus the designer of instructional environments or materials (including serious games) on the practical application of a theory.

2.5.1.1 Historical Theories of Learning

A number of theoretical perspectives on learning date back over 2,000 years. Here, two are examined because they are seen as underpinning many more modern perspectives on learning and represent a continuum (from an epistemological perspective) from the mind as a blank slate, to the mind (and its structures, mechanisms and processes) as the source of knowledge construction.

Empiricism takes the view that the human mind begins as a blank slate, often translated as *tabula rasa*. John Locke (1632-1704) used the term white paper or wax, which could "be moulded and fashioned as one pleases" (quoted in Ezell 1983). The view considers experience to be the primary source of knowledge with learning occurring through interaction with the environment (Schunk 2012). Since Aristotle (384-322 BC) and through others like Berkeley (1685-1753) and Hume (1711-1776) (Hjørland 2005), the view has contended that sensory experiences can be linked together over time to form complex structures—an example is a tree (a complex structure), which is built from branches and leaves, which are constructed from wood and fibre; the idea of a tree as this complex structure is built from the sensations of greenness (visual), woodiness (smell), and so on (example is from Hulse et al. 1980, described in Ertmer and Newby 1993).

Rationalism espouses the view that knowledge is the result of reasoning and not the senses (Schunk 2012). Using this perspective, the tree could be examined initially as a whole and then reflected upon to link aspects of it to prior knowledge. Ultimately, knowledge is acquired through the processes of the mind (for example, reasoning) rather than just experience. Among the best known rationalists are Plato (c.429-347 BC), Descartes (1596-1650), de Spinoza (1632-1677) and Leibniz (1646-1716), with Descartes being a major influence on Noam Chomsky (1928-) as cognitivism gained in popularity in the twentieth century (Hjørland 2005).

2.5.1.2 Behaviourism

The behaviourism approach to learning treats the learner as a black box—there are inputs (or stimuli) and outputs (observable performance). It was heavily influenced by the empiricist view of knowledge formation. Behaviourists believe that when learning occurs it is because of observable events in the environment (Schunk 2012). Little or no consideration in this approach is given to the internal mental workings of the learner (something which is a primary consideration of cognitivism, discussed in Section 2.5.1.3). One of the foremost proponents of behaviourism is B. F. Skinner (1953, 1969), whose theories were influenced by those of behavioural scientists such as John B. Watson (1924) and Ivan Pavlov (1927), both of whose scientific methods would raise serious ethical concerns by modern standards.

Pavlov performed many experiments on dogs while developing his theory of respondent conditioning (also known as classical conditioning) and the conditioned reflex. With respondent conditioning what would normally be a neutral stimulus becomes a conditioned stimulus when paired repeatedly with an unconditioned (or instinctual) stimulus that generates an instinctive reflex (one that is hard-wired in the cerebral cortex to respond to unconditioned stimuli). Eventually the unconditioned stimulus can be removed and the conditioned stimulus used to generate what now becomes the conditioned reflex. Watson for his part conditioned a phobia of furry animals in a baby (the so-called Little Albert experiment).

Another influence on Skinner was Thorndike, whose law of effect (part of his overall theory of connectionism and what would also become known as reinforcement theory) considers the consequence of a response (by a learner or non-learner) to be essential in strengthening the association between stimulus and response. He was not concerned with the mental processes or experience of the learner, but rather a trial-and-error process where various connections will be made between a stimulus and a response (known as the S-R bond) (Boakes 1984).

Skinner developed the theory of operant conditioning (also known as instrumental conditioning), which advocates negative and positive reinforcement where a learner's performance is unsatisfactory or satisfactory, respectively. These types of conditioning theories have generally proven to be effective when learning facts, definitions of concepts, making associations by applying explanations, and chaining a sequence of activities as part of a procedure. They are generally agreed, however, not to be as applicable to higher-order forms of learning, such as problem solving and critical thinking (Schunk 2012).

Behaviourist strategies in education include:

Instructional cues Instructional aids that help with student attention, comprehension and retention. They tend to boil down to a simple word, phrase or acronym the most important parts of a concept while not overburdening with unnecessary information. An example would be the use of a metaphor, such as when playing squash, the centre of the court is like a "magnet" drawing the player to it (Butler 2002). It is concise, precise and action-oriented.

Practice Leading to mastery that allows for progression to a more complex level of performance.

Reinforcement Tangible rewards and informative feedback.

Ertmer and Newby (1993) also list a number of ways in which behaviourist strategies have proven to be effective:

Discriminations Recalling facts.

Generalizations Defining and illustrating concepts.

Associations Applying explanations.

Chaining Automatically performing a specified procedure.

As they point out, however, these are not examples of higher-order thinking, associated with, for example, problem solving or critical thinking. Behaviourism is also limited in that it can explain how behaviours get changed, but it cannot account for how conceptual change happens (Yilmaz 2011).

2.5.1.3 Cognitivism

While behaviourism was the predominant perspective on learning in the first half of the twentieth century, the predominant perspective in the latter half of the twentieth century was cognitivism (Ertmer and Newby 2013). Cognitivism stresses knowledge acquisition and internal mental structures; while behaviourism is closely related to empiricism, cognitivism is closely related to rationalism (Ertmer and Newby 1993). However, compared to behaviourism, cognitivism is not as well understood by educators (Yilmaz 2011).

Cognitivism has its roots in cognitive psychology, which is concerned with "mental activities (such as perception, thinking, knowledge representation, and memory) related to human information processing and problem solving" (Shuell 1986). This is in contrast to behaviourism, which is concerned with behaviour, while cognitivism is concerned with meaning and semantics (Winn 2003).

Shuell (1986) defines cognitive approaches to learning as:

> an active, constructive and goal-oriented process that is dependent upon the mental activities of the learner.

That it is active is in contrast with the behaviourist perspective that treats the learner as a largely passive actor in the learning process. Shuell also writes that the cognitive approach focuses on the mental activities leading up to a response (rather than being merely concerned with the response being a correct behaviour in response to a stimulus). These mental activities include planning, goal setting and organizational strategies (these are explored more in Section 2.5.4). There is also an emphasis not just on knowledge being stored in memory, but on how the knowledge is used, particularly in new contexts (Ertmer and Newby 1993).

Of the leading cognitivist theories, Piaget's theory of individual cognitive development and Vygotsky's theory of social cognitive growth or zone of proximal development (covered in Section 2.5.5.7), have been the most influential and inspired the subsequent move towards constructivism (Yilmaz 2011). Piaget's theory is a largely Darwinian one—intellectual and cognitive development is like a biological act where the organism adapts to the environment. This lead to his theory that cognitive development happens in sequential stages. According to Piaget, equilibrium drives cognitive development: when we encounter new scenarios in the environment, we draw upon prior knowledge to understand the new scenario; when we are unable to use our present understanding, a state of disequilibrium in our mental schemata occurs requiring us to modify or reorganize our schemata (the process of adaptation). Two processes are involved: assimilation and accommodation; the former means integrating new information with existing knowledge, whereas the latter means a structural reorganisation of schemata (Yilmaz 2011).

The theory of *cognitive apprenticeship* (Brown et al. 1989) emphasizes the importance of the processes of a master and how the learner should be able to observe the master at work (modelling), and practice or explore the processes with the guidance of the master, who explains heuristics and procedural knowledge as the processes are carried out expertly. The master also acts as a coach, standing back and observing the learner and offering advice. The master can also scaffold the learning and slowly withdraw supports until the learner can perform the processes without assistance (this is similar to Vygotsky's zone of proximal development, discussed later).

A variation on this is social cognitive theory (SCT) (Bandura 1986), which proposes that there are cognitive processes that use the information that results from personal actions or from observing others carrying out actions. SCT has five forms of human functioning (descriptions of each are from Ponton and Rhea 2006):

Symbolization The ability to create mental images of temporary sensory experiences or information stored in long term memory;

Forethought The ability to use symbolization to create mentally unrealized future scenarios that provide motivation and desirable courses to pursue;

Vicarious learning The ability to learn from others—a mechanism that allows our society to continually advance the knowledge base by not wasting time relearning the same lessons but also eliminating serious safety risks in having to relearn lessons with life threatening consequences;

Self-regulation Enables a person to select and manage pertinent activities in order to realize goals;

Self-reflection A person's ability to think about the consequences of past experiences, thereby shaping subsequent beliefs, attitudes, intentions, and behaviours.

2.5.1.4 Constructivism

Constructivism is a branch of cognitivism, but differs from traditional cognitivism with respect to the function of the mind—cognitive psychologists tend to see the mind with reference to the real world, whereas constructivists see the mind as a filter of input from the real world to construct its own reality. Constructivism, therefore is individualistic—each person constructs their own personal version of the external world and information is interpreted in the context of prior experiences (Jonassen 1991).

This idea that reality is constructed and individualistic was proposed by Piaget, who broke with the traditional epistemological view that the pursuit of knowledge was the pursuit of an accurate picture of the real world (Von Glasersfeld 2005). Instead, humans create meaning rather than acquire it; this leads to the conundrum that there is no one "correct" meaning (Ertmer and Newby 1993).

Constructivist practitioners try to situate cognitive experiences in authentic activities. Every experience with an idea and its situated context both become part of the meaning of the idea. Many constructivist theorists point to a common problem with school-based learning: that it is not situated in an authentic environment, thus transfer of learning is more limited (Duffy and Jonassen 2013). Many constructivists describe authentic learning environments as ones where the learning is conducted in an environment that closely simulates real world complexities and occurrences (e.g. Herrington and Oliver 2000), itself an idea founded in the theory of situated cognition of Brown et al. (1989) and Lave's (1991) communities of practice and shared cognition. The idea that you could have information that is "inert", decontextualised or "welded to its original occasion of use" runs counter to the idea of an authentic learning environment.

Biggs (1996) marries the perspectives of learning theory, particularly constructivist, and instructional design with constructive alignment. The three points of the constructive alignment triangle that drive the decision-making of instructional design are:

1. Curriculum objectives that bring learners to a sufficiently high-level of learning;
2. Teaching and learning activities to achieve the objectives;
3. Assessment of student performance (including summative).

Walsh (2007) simplifies the process of constructive alignment by proposing three questions for the educator to answer:

- What should the student be able to understand/perform at the end of the learning experience?
- What activities would the student have to undertake in order to learn this?
- How can the tutor find out if the student has learned successfully?

Problem-based learning (PBL) is part of the constructivist tradition and has an emphasis on self-directed learning and a stimulating environment that helps learners restructure information they already know to gain new knowledge (and apply it in a new context)—it sets the context as an approach to learning more so than teaching (Engel 1992). In that sense, it can be considered a student-centred approach. The concept first appeared in print in Barrows and Tamblyn (1980). However, what exactly PBL entails nowadays can be difficult to define (Taylor and Miflin 2008), though there is general agreement at a base level that "it is an approach to structuring the curriculum which involves confronting students with problems from practice which provide a stimulus for learning" (Boud and Feletti 2013). Some studies have shown how PBL enhances critical thinking in comparison to traditional teaching methods (e.g. Tiwari et al. 2006). Supporters of PBL point to its highly-motivating environment and how this enhances learning, while others bemoan how time consuming it is or the lack of evidence to back up its effectiveness (Kilroy 2004).

2.5.1.5 Connectivism

A number of theoretical perspectives have emerged in the twenty-first century with the dawn of the internet age and more recent advances such as Web 2.0, social media and ubiquitous smart devices (Ertmer and Newby 2013, Dunaway 2011). While they have not yet become widely accepted, they are nonetheless worth briefly exploring given the increasingly networked environment we live in and the push in the education sector towards the use of technology for collaboration. One of those theories, connectivism, is discussed here.

The theory of connectivism was proposed by Siemens (2004). Connectivism has at its root the general theory that learning is based on the making of connections and traversing those connections, just like network traffic on the internet. The connections occur on neural, conceptual and social levels. In an increasingly digital age, learners become researchers and must discriminate between information that is important or unimportant. Chaos (the connection of everything to everything) is becoming the new norm for knowledge workers.

Siemens notes the following trends in learning:

- Many learners will move among a variety of often unrelated fields of work over their lifetimes.
- Learning will occur in many ways, more often than not in an informal way—person networks, communities of practice, work-related tasks.
- There is an emphasis on lifelong learning with less separation between formal and work-based education.
- Technology is altering our brains.
- We can offload many cognitive processes to technology.
- Know-where is supplementing know-how and know-what.

To counter this, he notes that learning can no longer be just internal and must extend to augment the individual with the ability to access a network of knowledge. Knowing how to access the network to plug into resources is becoming a vital skill.

2.5.2 Learning Preferences

No two students learn in exactly the same way and students will respond to or benefit from different teaching styles (Gargiulo and Metcalf 2016). There have been a number of catalogues or lists (as part of a model) of learning styles developed over the last several decades (Hall and Mosely 2005). Many of these were developed based on assumptions about learning from various fields of research, such as brain function, and various branches of psychology, such as fixed personality traits and intellectual ability (Coffield et al. 2004). It should be noted that while there are several models of learning style based on fixed personality traits, often accompanied by questionnaires (some of them available online and some for a fee if they are being used commercially) that match you to a learning style based on your responses, this may lead to a narrow view that a teaching style can easily be found for a learner's singular learning style (a problem of labelling). There is also a lack of research on the effectiveness of teaching to the styles in these indexes (Gargiulo and Metcalf 2016, p.42).

The number of available learning styles inventories is very large. For example, Hall and Mosely (2005) analysed more than 50 before narrowing down the list, using four criteria, to a shorter list of 13. Three indexes / inventories / catalogues, chosen because their types or preferences are continuums rather than fixed labels, are included here with original brief explanations from the cited sources.

- The Felder and Silverman (1988) Learning Styles Index, which has four dimensions, each of which is a continuum:
    - *sensing* (concrete thinker, practical, oriented toward facts and procedures) or *intuitive* (abstract thinker, innovative, oriented toward theories and underlying meanings);
    - *visual* (prefer visual representations of presented material, such as pictures, diagrams and flow charts) or *verbal* (prefer written and spoken explanations);
    - *active* (learn by trying things out, enjoy working in groups) or *reflective* (learn by thinking things through, prefer working alone or with a single familiar partner);
    - *sequential* (linear thinking process, learn in small incremental steps)

or *global* (holistic thinking process, learn in large leaps).

- The Kolb Learning Style Inventory (Kolb and Kolb 2011) has emerged from David Kolb's earlier research on experiential learning theory (ELT) and the cycle discussed in Section 2.5.5.6. Each learning style emphasizes two or three stages of the experiential learning cycle (active experimentation, concrete experience, abstract conceptualization and reflective observation) to different degrees (a two-dimensional or three-dimensional continuum). The version 4.0 learning styles are:
  - The *Initiating* style is distinguished by the ability to initiate action to deal with experiences and situations.
  - The *Experiencing* style is distinguished by the ability to find meaning from deep involvement in experience.
  - The *Creating* style is distinguished by the ability to create meaning by observing and reflecting on experiences.
  - The *Reflecting* style is distinguished by the ability to connect experience and ideas through sustained reflection.
  - The *Analyzing* style is distinguished by the ability to integrate and systematize ideas through reflection.
  - The *Thinking* style is distinguished by the capacity for disciplined involvement in abstract reasoning, mathematics and logic.
  - The *Deciding* style is distinguished by the ability to use theories and models to decide on problem solutions and courses of action.
  - The *Acting* style is distinguished by a strong motivation for goal directed action that integrates people and tasks.
  - The *Balancing* style is distinguished by the ability to flexibly adapt by weighing the pros and cons of acting vs. reflecting and experiencing vs. thinking.
- The learning preferences model presented in Winebrenner (2009), which is influenced by Gardner's (1983) Theory of Multiple Intelligences (touched upon in Section 2.4.2.1 when discussing VR's affordance to bodily-kinaesthetic learning). Table 2.12 is an adaptation of Winebrenner's from Gargiulo and Metcalf (2016), which is a book that

describes the UDL framework, and makes the point that for education to be inclusive, we need to cater for multiple learning preferences.

Table 2.12: Learning Preferences from Winebrenner (2009)

Type of Learner	**Learning Characteristics**
Visual/Verbal	Prefers receiving visual information paired with print
	Visualizes information to be learned
	Likes to study in a quiet room
Tactile/Kinaesthetic	Prefers hands-on activities
	Prefers hands-on learning
	Active, learns through physical movement training
Visual/Nonverbal	Prefers information presented visually
	May be artistic
	Tends to prefer a quiet room rather than study groups
	Uses visual pictures to remember
Auditory/Verbal	Prefers listening to a lecture
	Learns best though interaction with others—exchanging ideas
	Uses what is heard to remember and may repeat information out loud

It should be noted, however, that while learning style / preference inventories can be useful as a means of thinking about the types of learning that might take place and how a variety of them could increase inclusivity, they have been criticised. Section 2.4.2.1 provided a summary of criticisms by Peterson et al. (2009). More recently Coffield (2013) criticised learning styles in four ways:

1. Incoherence and conceptual confusion; for example overlapping learning styles and ones that lack "scientific justification".
2. There was a wide range of quality in the learning style inventories reviewed.
3. They lack context; for example, a learning style applied to a plumber will

not be the same as for a hairdresser. The implied suggestion by Coffield is that if one was to have an inventory of learning styles, that it should be both content and context relevant.

4. There is a lack of evidence that learning is improved by tailoring teaching for individual learning styles.

Coffield was a signatory along with 29 other eminent scholars to a 2017 letter to *The Guardian* newspaper[9] bemoaning what they termed a *neuromyth* lacking evidence. They hint at the issue of labelling discussed earlier in this section when they write that "categorising individuals can lead to the assumption of fixed or rigid learning style, which can impair motivation to apply oneself or adapt."

It is perhaps wise, therefore, to consider learning preferences within a holistic approach to teaching and learning (for example, in conjunction with a framework such as universal design for learning and various theories of learning, such as the experiential learning cycle, both of which are discussed in later sections) rather than being means unto themselves.

2.5.3 Student-centred Learning

The concept of student-centred learning (SCL) represents a shift from a teacher-centred or content-oriented approach to a learner-centred or learning-oriented one; the lecturer becomes more of a facilitator of learning and allows for students to construct their knowledge rather than a didactic approach where the lecturer merely transmits information (Kember 1997). What links the two, according to Kember, is student-teacher interaction. This facilitation by the educator could be in person, or with the aid of modern technology, for example by engaging via social media channels or through digital content that the lecturer has either sourced (the idea of the educator as a curator of digital artefacts) or created (such as with a serious game).

Lea et al. (2003), having reviewed the literature on student-centred learning, provide a list of tenets that are embodied by SCL:

- reliance upon active rather than passive learning;
- an emphasis on deep learning and understanding;

[9] See https://www.theguardian.com/education/2017/mar/12/no-evidence-to-back-idea-of-learning-styles

- increased responsibility and accountability on the part of the student;
- an increased sense of autonomy in the learner;
- an interdependence between teacher and learner;
- mutual respect within the learner–teacher relationship;
- a reflexive approach to the learning and teaching process on the part of both teacher and learner.

Context is another important consideration in SCL. The constructivist approach, as outlined earlier, emphasizes that knowledge and context are linked (Hannafin et al. 1997), requiring that the educator understand how individual each learner is. Hannafin et al. describe the idea of an open-ended learning environment (OELE) where there is an emphasis on “learning contexts embedded in authentic problems”, the opportunity to “manipulate, interpret and experiment”, and approaches that are centred around “wholes” (a synonym they use for higher-order concepts). They also emphasise “meaningful problems” linked to “everyday problems”.

There are, though, potential problems with SCL—it can be labour intensive and some students who have been used to a didactic content-delivery approach will initially be resistant to change (Felder and Brent 1996).

Not every approach to facilitating student learning will satisfy all of those tenets, but rather a combination of tools and approaches. A serious game will have some deficits in terms of SCL: for example, because a computer-based serious game is labour-intensive, the chance for students to negotiate what and how they learn is more limited. A reflective DGBL designer will research student experiences and outcomes to refine a game over time, perhaps through several iterations of a course of study. But the more flexible the implementation of the DGBL, the greater the opportunity for negotiation with the learner. These are the realities of taking a universal design for learning approach (as discussed in Section 2.7) to the design of DGBL solutions, which is a truly student-centred approach.

2.5.4 Metacognition, Learner Autonomy and Open Inquiry

Flavell (1979) describes metacognition as follows:

> Metacognitive knowledge is one's stored knowledge or beliefs about oneself and others as cognitive agents, about tasks, about actions or strategies, and about how all these interact to affect the outcomes of any sort of intellectual enterprise. Metacognitive experiences are conscious cognitive or affective experiences that occur during the enterprise and concern any aspect of it——often, how well it is going.

To put it another way Flavell (1979) is saying that metacognition is the way we are consciously aware of our thoughts to the extent that we can analyse them and evaluate them. This is true of our thoughts about our learning. However, Schoenfeld (2009) points out that definitions of metacognition can be varied and almost contradictory: it can mean “knowledge about one's own thoughts”, or it can mean “self-regulation during problem solving”.

In Flavell's description of metacognition, he specifically mentions the person evaluating “how well [a task] is going”. Evaluating how well something is going is relative: how well is it going compared to what? Metacognition, therefore is closely related to the concepts of self-regulation and goal setting. Goal setting, according to Vohs and Baumeister (2016, p.595) is the first process of goal pursuit (the second being goal striving, the carrying out of the actions to achieve the goals set). As far as self-regulation goes, goal setting allows people to define levels of performance that should be adhered to (Bandura 1993). Goals have two aspects: achievability and specificity (Vohs and Baumeister 2016); achievability is how easy or difficult the goal is, whereas specificity is how concrete the goal is (for example, becoming more knowledgeable about a subject is an abstract goal, whereas getting a first-class honours grade in a subject is something concrete).

Closely related to self-regulation is the concept of learner autonomy, which is described as when learners take on responsibility for their own learning—in making decisions about learning and implementing the decisions (Boud 2012), one form of which is goal setting and goal striving. Autonomous learners consider themselves to be in control with an intrinsic motivation to learn and an ability to be more active and independent in their learning—personal autonomy, according to Lebow, is one of the five principles of constructivist instructional design (Lebow 1993), which in turn is fundamental to what are called rich environments for active learning (REALs) (Grabinger and Dunlap 1995), of which the graph game is arguably an example. Lebow writes, though, that while personal autonomy means giving more control to the learner, an element of stewardship is required—in other words, autonomy does not equal permissiveness. Kirschner et al. (2006) argues against a light touch approach, instead arguing for the evidence behind the superiority of guided instruction (particularly where the learner has little prior knowledge). Therefore, a balance (guided by context) of providing a guiding framework (such as a game with levels and instructions) with sufficient opportunity for autonomy appears to be the best approach.

Learners being more autonomous might be desirable, but it is something that educators have to foster, and this is particularly true in the sciences where a sense of curiosity and experimentation are desirable (Zion and Sadeh 2007). The search for knowledge has three levels of inquiry: structured, guided and open (Colburn 2000). The latter is the most demanding and the educator merely sets the context for the inquiry and the learner identifies problems and solves them. Open inquiry can also lead to more active learning and promote learner autonomy (Hodson 2009, quoted in Bjønness and Kolstø 2015).

2.5.5 Instructional Design

2.5.5.1 Introduction

This section on instructional design culminates in a review of models of instructional systems design (ISD), but before it gets there, it covers some models, frameworks and approaches to teaching and learning that inform the ISD process.

In explaining what instructional design is, Gustafson and Branch (2002) provide a list of characteristics that should be present in all instructional design activities:

1. Instructional design is learner-centred;
2. Instructional design is goal-oriented;
3. Instructional design focuses on real-world performance;
4. Instructional design focuses on outcomes that can be measured in a reliable and valid way;
5. Instructional design is empirical;

6. Instructional design is typically a team effort.

The list appears to be almost future-proofed with its focus on the learner at the centre of the process (the student-centred approach to teaching and learning was discussed in Section 2.5.3), the use of empirical data to validate the approach, the use of teams and, earlier in their chapter, a focus on instructional design that is “iterative and self-correcting”, features that will be covered in Section 2.6 on agile software development. The list is also a check-list to apply to any new model, including the proposed adaptive model presented in Chapter 3. The following subsections support some of the listed characteristics.

Sections 2.5.5.2 and 2.5.5.3 provide ways in which what is to be learned can be structured and more easily measured using taxonomies. The revised Bloom’s taxonomy is the most widely used taxonomy of learning, but Biggs’s SOLO taxonomy has some distinct advantages over it and is used later in the graph game (Chapter 4). There are numerous other taxonomies, such as Gagné’s taxonomy of five learning outcomes (Driscoll 2005, p.350), some of them domain specific (e.g. Fuller et al. 2007, for computer science), and while they have advantages, there are some criticisms of them. They map neatly to the metaphor of a linear learning path, but learning is not always linear and so they need to be used in the context of other pedagogical considerations, some of which are covered in later sections.

At the heart of both taxonomies is the *learning outcome*. *Intended* learning outcomes (ILOs) are the ones that educators assign verbs to, that are clearly defined and appear in module descriptions. From Biggs’s (2002) perspective (that of constructive alignment), an ILO would involve learners constructing meaning “through relevant learning activities”. According to Brown (2019), ILOs should be VASCULAR (Verifiable, Action orientated, Singular, Constructively aligned, Understandable, Level-appropriate, Affective-inclusive, and Regularly reviewed). However, ILOs are distinct from what one might term unintended learning outcomes, or hoped-for learning outcomes. These are what Race (2018) calls *emergent* learning outcomes, which for students could include (in Race’s own words):

- things they learned about the subject concerned above and beyond what we intended them to learn;
- things they learned about the links between our subject and other

subjects they are learning;

- things they learned by getting things wrong on their journey towards achieving the intended learning outcomes;
- things they learned about themselves as learners – for example, techniques they developed while learning this particular bit of curriculum which will be useful to continue to apply to other learning contexts;
- things they learned from each other, and skills they gained in working with each other.

Section 2.5.5.4 covers the distinction between an outcome-oriented approach to teaching and learning (which is behaviourist) versus a process-oriented approach and makes a case for both to be included. Biggs's SOLO taxonomy is an attempt to incorporate both approaches, particularly if one considers SOLO and Biggs's concept of constructive alignment as a natural pairing, whereas Bloom's taxonomy is considered largely behaviourist (for a discussion, see Murtonen et al. 2017).

A number of theories of learning that can be used to structure learning are explored. This includes Bruner's spiral curriculum (Section 2.5.5.5), Kolb's experiential learning cycle (Section 2.5.5.6) and Vygotsky's zone of proximal development (Section 2.5.5.7). Other approaches are touched on throughout the thesis, such as Biggs's constructive alignment (see Section 2.5.1.4) and Gagné's nine elements of instruction (Section 2.5.5.8). The field of pedagogy is vast and it is not possible to include them all, but an attempt has been made to cover many of the more popular theories.

Section 2.5.5.8 lists and describes several models of instructional systems design, which will inform the development of the adaptive model for DGBL.

2.5.5.2 Bloom's Taxonomy

Bloom's taxonomy, originally known as the taxonomy of educational objectives published in Bloom et al. (1956), is a hierarchical classification that is one of the most widely cited in the curriculum development field (Seaman 2011). Though it is most closely associated with Benjamin Bloom, Seaman points out that there were many participants in conferences on the taxonomy between 1949 and 1953 and that those participants and Bloom's mentor, Ralph Tyler, played a role in refining what became the 1956 version. It is often linked to the behaviourist perspective because the handbook describes the taxonomy as a classification of student behaviours linked to learning outcomes.

The 1956 one-dimensional taxonomy of educational objectives, with its hierarchy beginning with knowledge at the base and evaluation at the peak (see Table 2.13 for the full taxonomy including the subcategories, which are the specific cognitive processes), was revised by Anderson and Krathwohl (2001) who produced a two-dimensional taxonomy (often referred to as the revised Bloom's taxonomy). Rather than knowledge being at the base of the hierarchy, it became its own dimension (to add to the cognitive process dimension).

The original taxonomy was seen as being cumulative so that, for example, being able to evaluate meant that you first had to be able to synthesise. An ability to synthesise was based on an ability to analyse, and so on. Curricula and assessments, therefore, would aim to move the learner from the level of basic knowledge (often associated with rote learning) to at least comprehension and ideally to the levels of analysis, synthesis and evaluation, which represent higher orders of thinking.

The revised taxonomy revisited the knowledge subcategories and left them largely intact while adding a meta-cognitive category (see Table 2.14), which is about self-awareness.

It then used the knowledge category instead as a new dimension, creating a matrix of levels of knowledge versus revised levels of cognition (see Table 2.15 for the revised taxonomy's matrix with cognition on the x-axis). For example, one could have a knowledge of specific algorithms (under the conceptual knowledge category of the knowledge dimension) and be able to apply them (the apply category of the cognitive process dimension), but not be able to analyse (break the algorithm down into its constituent components and understand the relationships among the components), which would mean by extension that selecting one algorithm over another (the evaluate category of the cognitive process dimension) would be beyond the learner also. It is also possible to be less granular and to refer to just the high-level categories of the dimensions—how granular to be will depend on factors such as whether you are examining an entire programme, a module / subject, or a single learning outcome or assessment. Like the original taxonomy, the revised taxonomy is cumulative, but across two dimensions, ideally reaching the bottom-right of the matrix (D6) for the highest level of learning.

Table 2.13: Bloom's Taxonomy of Educational Objectives

1.0 KNOWLEDGE
1.10 Knowledge of Specifics
1.11 Knowledge of Terminology
1.12 Knowledge of Specific Facts
1.20 Knowledge of Ways and Means of Dealing with Specifics
1.21 Knowledge of Conventions
1.22 Knowledge of Trends and Sequences
1.23 Knowledge of Classifications and Categories
1.24 Knowledge of Criteria
1.25 Knowledge of Methodology
1.30 Knowledge of the Universals and Abstractions in a Field
1.31 Knowledge of Principles and Generalizations
1.32 Knowledge of Theories and Structures
2.0 COMPREHENSION
2.1 Translation
2.2 Interpretation
2.3 Extrapolation
3.0 APPLICATION
4.0 ANALYSIS
4.1 Analysis of Elements
4.2 Analyses of Relationships
4.3 Analysis of Organizational Principles
5.0 SYNTHESIS
5.1 Production of a Unique Communication
5.2 Production of a Plan, or Proposed Set of Operations
5.3 Derivation of a Set of Abstract Relations
6.0 EVALUATION
6.1 Evaluations in Terms of Internal Evidence
6.2 Judgements in Terms of External Criteria

Reproduced from Bloom et al. (1956).

Table 2.14: Knowledge Dimension of the Revised Bloom's Taxonomy

A. Factual Knowledge — The basic elements that students must know to be acquainted with a discipline or solve
Aa. Knowledge of terminology
Ab. Knowledge of specific details and elements
B. Conceptual Knowledge — The interrelationships among the basic elements within a larger structure that enable them to function together
Ba. Knowledge of classifications and categories
Bb. Knowledge of principles and generalizations
Bc. Knowledge of theories, models, and structures
C. Procedural Knowledge — How to do something; methods of inquiry and criteria for using skills, algorithms, techniques, and methods
Ca. Knowledge of subject-specific skills and algorithms
Cb. Knowledge of subject-specific techniques and methods
Cc. Knowledge of criteria for determining when to use appropriate procedures
D. Metacognitive Knowledge — Knowledge of cognition in general as well as awareness and knowledge of one's own cognition
Da. Strategic knowledge
Db. Knowledge about cognitive tasks, including appropriate contextual and conditional knowledge
Dc. Self-knowledge

Reproduced from Anderson and Krathwohl (2001).

Table 2.15: The Revised Bloom's Taxonomy Matrix

The Knowledge Dimension	1.Remember	2.Understand	3.Apply	4.Analyze	5.Evaluate	6.Create
A.Factual Knowledge						
B.Conceptual Knowledge						
C.Procedural Knowledge						
D.Metacognitive Knowledge						

Reproduced from Bloom et al. (1956).

There have been a number of further adaptations of the revised taxonomy and lists of verbs associated with the cognitive process dimension, in particular, have been drawn up. Table 2.16 is reproduced from the Oregon State University (OSU) course development website (Oregon State University 2011). The table is provided on the website as part of its guidance for writing learning outcomes, with each cell in the matrix providing a sample verb to use when constructing a learning outcome. It goes further than many lists of verbs associated only with the cognitive process dimension by further aligning them with the knowledge dimension.

Table 2.16: Oregan State University Matrix

The Knowledge Dimension	*Remember*	*Understand*	*Apply*	*Analyze*	*Evaluate*	*Create*
Factual Knowledge	List	Summarize	Classify	Order	Rank	Combine
Conceptual Knowledge	Describe	Interpret	Experiment	Assess	Assess	Plan
Procedural Knowledge	Tabulate	Calculate	Calculate	Conclude	Conclude	Compose
Metacognitive Knowledge	Appropriate Use	Construct	Construct	Action	Action	Actualize

Sample learning outcomes for each verb are provided, such as for *List*: "To identify the names, professional identities, and ideas of two or three of the major western sexologists", and *Actualize*: "Engage in activism on behalf of social justice for women." This demonstrates a progression from low-order thinking (regurgitating facts) to high-order thinking (being self-aware enough to understand how one could effect change in local or global systems).

There have been numerous critics of Bloom's taxonomy. Seaman (2011) outlines some of these:

- Its linearity is a blessing and a curse: while it is a simplistic (and therefore practical) view of learning that begins with remembering and ascends a hierarchy into high-order thinking, this is not how learning really happens (the revised version is less strict about the hierarchy).
- Because it is so widely used (sometimes mandated), educators tend not to question its use or appropriateness.

Fuller et al. (2007) proposes using Bloom's taxonomy in a spiral. This is similar to Bruner's spiral curriculum, though at a more micro level; the spiral curriculum, as the name suggests, spans an entire curriculum (and is thus more macro) potentially composed of multiple modules, whereas using Bloom's taxonomy as a spiral would be at the level of the single learning outcome.

A notable addition to Bloom's taxonomy is the Bloom's Digital Taxonomy (Churches 2007). It recognises the emergence of the *digital native*, those people born after 1980 when the networked computer became a phenomenon (Palfrey and Gasser 2011). For many digital natives, new modes of digital learning have become second nature, such as blogging, hacking, reverse engineering, tagging (with metadata), mashing, linking, podcasting and programming. Churches offers these and other verbs mapped to the thinking skills of the revised Bloom's taxonomy. Advanced game engines can provide capabilities that allow learners to engage in the digital thinking skills that Churches proposes, and this makes his digital taxonomy worthy of consideration when constructing learning outcomes.

2.5.5.3 Biggs's SOLO Taxonomy

The SOLO Taxonomy (Structure of the Observed Learning Outcome) (Biggs and Collis 1989) is influenced by Piaget's theory of stage development. It is relatively easy to map the five stages (pre-operational, early concrete, middle concrete, concrete generalizations and formal) to the five levels of the SOLO taxonomy (see Table 2.17). While stage theory is related to child development (for example that a seven-year-old child might be able to understand a single operation, such as counting the length of something, but would not be capable of the same level of understanding as a ten-year-old who can use two operations, counting length and width to judge an area), the SOLO taxonomy is concerned with learning quality (assuming a learner with a stable IQ over the course of the learning). Where the two diverge is in labelling—in stage theory a child is given a label, such as pre-operational or middle concrete, and this is fixed until the child reaches the next stage of development (or stops at formal). With SOLO, it is the level of understanding of an abstract concept that is labelled. A learner may have reached the relational level with one concept, yet be at the uni-structural level of another; the learner may be capable of reaching an extended abstract understanding of one concept, but be incapable (because of learner IQ or difference in difficulty) of reaching that level with another.

Table 2.17: Biggs's SOLO Taxonomy

Prestructural	The task is engaged, but the learner is distracted or misled by irrelevant aspects or information; nothing meaningful has been learned.
Unistructural	The learner focuses on the relevant domain, and picks up one aspect to work with; one specific thing has been learned.
Multistructural	The learner picks up more and more relevant or correct features, but does not integrate them; several relevant, independent and meaningful aspects have been learned.
Relational	The learner now integrates the parts with each other, so that the whole has a coherent structure and meaning; aspects learned are integrated into a structure.
Extended Abstract	The learner now generalises the structure to take in new and more abstract features, representing a higher mode of operation; aspects learned are generalised to a new domain.

Biggs and Collis (1989)

An example of the application of the SOLO taxonomy was in a study by Sheard et al. (2008). A study of introductory programming students examined their responses to three questions in an exam. Two of the questions asked the students to: "Explain the purpose of the following code". The SOLO taxonomy was used to analyse the responses.

An example question from the Sheard et al. study was to explain the purpose of the following code:

```
a = b;
b = c;
c = a;
```

A multi-structural structural response might explain that the code assigns the values of variables to other variables—a number of concepts, such as variables and assignments, are integrated. A relational response, though, would recognise that the purpose of the code is to swap the values of variables *b* and *c* (and that *a* is a temporary variable). If the students were to demonstrate extended abstract understanding, a follow up question might have presented a scenario without mentioning a swap was required and students would have been required to apply their swap knowledge in this new scenario.

Sheard et al. were able to code the student responses using the SOLO taxonomy and make findings such as there being a statistically significant difference in the level of understanding demonstrated by postgraduate and undergraduate students—for the swap question 80% of postgraduates demonstrated a greater than multi-structural level of understanding compared to 30% for undergraduates (the difference was significantly less for the other two questions).

A more in-depth explanation of what constitutes a particular SOLO level of understanding is provided by Lister et al. (2006), which the Sheard et al. study was based on. For example, the authors state that a multi-structural response is where the student understands the individual constructs and step-by-step mechanics of a code example, but cannot “see the forest for the trees”—in other words they cannot see the higher purpose of the code.

The SOLO taxonomy, like other taxonomies, can be used as a means of gauging learner progression. For example, Halloran (2008) uses the SOLO taxonomy as a hierarchy to inform students about their progress through various learning mechanisms that increase understanding—moving from two-minute questions in class (uni-structural), to questions in an online discussion board (multi-structural to relational), to tutorials featuring a deeper discussion (relational to extended abstract), to an individual reflective journal (extended abstract).

2.5.5.4 Behaviourism and Outcome Versus Process Orientation

According to Kolb and Kolb (2005), experiential learning theory (part of the constructivist tradition) posits that learning is better thought of as a process rather than something that should be driven by outcomes. The behaviourist approach to learning is outcome-driven.

Biggs claims that while his theory of constructive alignment is a form of outcomes-based education (OBE), it should not be confused with some forms of OBE that have been abused to serve a “managerial agenda” (Biggs n.d.). Instead, Biggs would argue that his theory of constructive alignment embodies both the best of outcome- and process-oriented approaches to learning; the focus with SOLO, for example, is on the quality of outcome and how the learning (that is, the process) supports that. However, constructive alignment, based as it is on outcomes, is not without criticism. Addison (2014), for example, argues that whereas constructive alignment privileges the outcome, Vygotsky's theories (see Section 2.5.5.7) privilege mediation or emergence (though he notes Biggs's acknowledgement of unexpected or emergent LOs, which Addison writes "remain peripheral" to constructive alignment). Section 2.5.5.1 provides a description of emergent learning by Race (2018).

The relationship between process and outcomes is a close one. For example, Marton and Säljö (1997) recount their study of student outcomes and found they were closely correlated with a deep level of learning—those students attaining an A or B grade were associated with deep approaches to learning and those with C and D grades with surface level approaches to learning. A further study by Rossum and Schenk (1984, discussed in Marton and Säljö 1997) using Säljö's five conceptions of learning (Saljo 1979), found a similar clear split between surface learners (those whose conceptions of learning were one of increase in *knowledge*, *memorisation* and *fact acquisition for utilisation*) and deep learners (those whose conceptions of learning were one of *abstraction of meaning* and *understanding reality*), though the study was process- rather than outcome-focused. However, if the desired outcome is to go beyond an abstraction of meaning and into the realm of understanding reality (in line with SOLO's extended abstract LO), then one could read into that study that promoting a deep approach to learning will best attain that outcome.

Biggs (1987) introduces another approach to learning (alongside deep and surface), that of *achieving*, which he describes as being motivated by competition or ego enhancement. The objective of the achieving learner is to be the best in class in terms of grades whether interested in the subject matter or not.

To summarise, it should not be a question of being either outcome- or process-focused—the two go hand in hand—but rather encouraging a deep approach to learning to attain the best student outcomes. These outcomes could be intended (behaviourist) or emergent (more in the cognitive or constructive traditions, with additional reference to affective or psychomotor domains).

2.5.5.5 Bruner's Spiral Curriculum

Bruner's spiral curriculum concerns the structure of content and the overall curriculum (Harden 1999). In that sense, it is a global approach to education that spans multiple modules of learning. It is an iterative approach where concepts are revisited, but in an ever deeper way. Bruner outlines, in a way that is similar to a progression through a taxonomy such as SOLO, how ideas and operations are introduced at an intuitive level and progressively and iteratively re-introduced until there is mastery at an abstract and comprehensive level, ultimately with the mastery of an entire body of knowledge (and its complexity in terms of structure and interconnectedness) (Bruner 1960).

Harden (1999) summarises the features of the spiral curriculum as follows:

1. Topics are revisited;
2. There are increasing levels of difficulty;
3. New learning is related to previous learning;
4. The competence of students increases.

This suggests that the spiral curriculum is primarily constructivist, but it is also closely related to cognitivism. For example, in a study of dental students (Coelho and Moles 2016) who had gone through a four-year spiral curriculum, an analysis of survey comments showed that students found that their knowledge was "cemented", that they "had gone from memorising to understanding", and that they found revision easier. One of the themes that emerged from the analysis was an enhancement in cognitive functions, such as memory, understanding and confidence.

2.5.5.6 Kolb's Experiential Learning Cycle

The experiential learning cycle is built upon the theories of Dewey, Lewin, Piaget, James, Jung, Freire, Rogers and more (Kolb and Kolb 2005). It is process rather than outcome focused. Learning, Kolb and Kolb (2005) write, involves "the integrated functioning of the total person—thinking, feeling, perceiving, and behaving". It is a constructivist theory according to the authors.

There are four stages in the cycle. The first is the *concrete experience* after which the learner enters into *reflective observation* about the experience. The learner then builds an *abstract conceptualisation*, consisting of generalisations and hypotheses, and tests them through *active testing*.

Figure 2.11 shows the experiential learning cycle mapped to areas of the cerebral cortex. For example, when the learner is in the active testing stage of the cycle, the motor and premotor segments of the cerebral cortex are activated. Zull (2002) writes that “learning is physical” in the sense that it causes physical changes in the brain. True learning, he writes, requires activation of each area of the cortex and therefore good teaching will result when it activates the four areas.

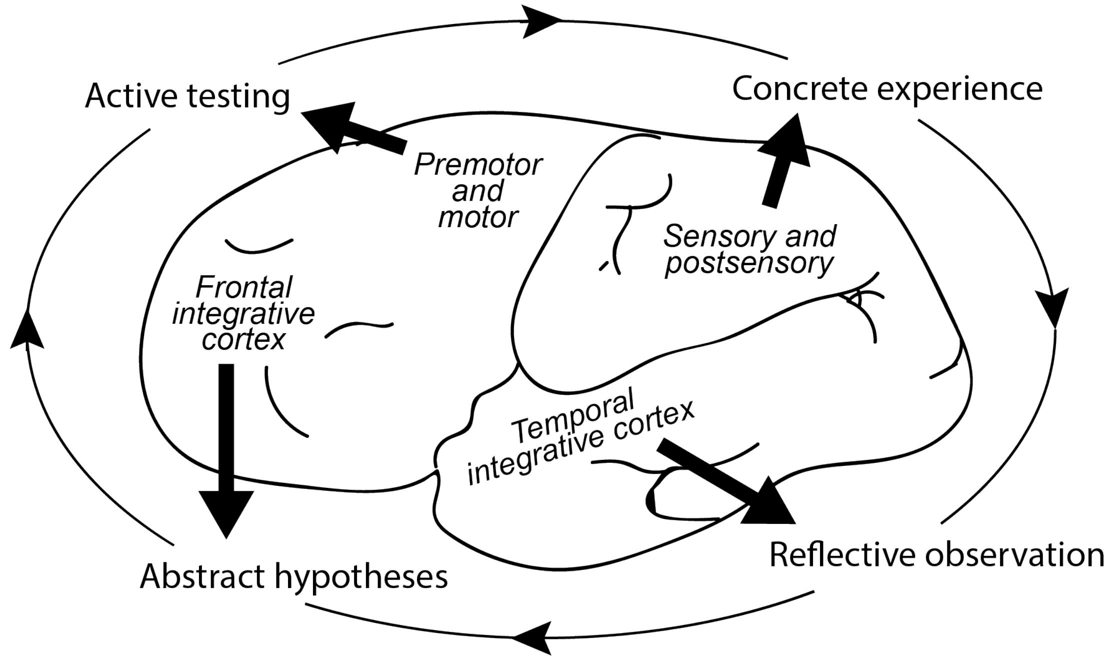


Figure 2.11: The experiential learning cycle mapped to regions of the cerebral cortex (image reproduced from Zull 2002)

The theory has frequently been applied to DGBL, such as the experiential gaming model that features an ideation loop, an experience loop and a challenge bank (Kiili 2005). Kiili likens the model to a vascular system with ideas circulating like blood and the challenges representing the heart of the system. The player tests solutions in an experience loop, observing and reflecting upon the outcomes.

2.5.5.7 Vygotsky's Zone of Proximal Development and the Practice of Scaffolding

Vygotsky (1978, p.86) defines the zone of proximal development (ZPD) as:

> the distance between the actual developmental level as determined by independent problem solving and the level of potential development as determined through problem-solving under adult guidance, or in collaboration with more capable peers.

Essentially, the ZPD is that area between what the learner knows or does not know. It is an area where the learner is capable of learning what is in the area with the guidance and encouragement of an instructor. This zone is often regarded as representing the *potential* of a learner to learn, but as Kozulin et al. (2003, p.42) points out, it is not the zone of proximal *learning* but of *development*; it is not just a zone that must be identified to allow learners progress effortlessly in their learning, rather it also includes the development of a capacity for learning (the how) rather than just the learning itself (the what). Vygotsky did not see learning as something taking place just *within* the learner, but as something that has social and collaborative dimensions and therefore learning is something that happens *between* individuals (Gibbons 2015).

Although Vygotsky never mentioned the word, the term *scaffolding* is often used in relation to the ZPD. The term was first used in a pedagogical context by Wood et al. (1976) when referring to the development of speech in children. They defined scaffolding as something "that enables a child or novice to solve a task or achieve a goal that would be beyond his unassisted efforts." The concept of scaffolding in a pedagogical context is not dissimilar to the lay person's understanding of scaffolding—that it supports something, such as a building, as Gibbons (2015) explains. As the building work is carried out, so the scaffolding is slowly removed until the building can stand by itself. The same is true of scaffolding with respect to teaching and learning. It is something that is temporary but necessary and only when the learner demonstrates the capacity to accomplish a task unaided does the instructor remove the support. Thus, the learner eventually becomes more autonomous.

2.5.5.8 Models of Instructional Systems Design

One definition of instructional systems design (ISD) is:

> a system of procedures for developing education and training programs in a consistent and reliable fashion. (Gustafson and Branch 2002)

Other terms abound, such as instructional development and instructional design and the origins of ISD can be traced to the military during World War II (Reiser 2001). Gagné et al. (1992) distinguish between two phases of instructional design that should be performed separately: the immediate occurs in the hours before instruction, such as the construction of a lesson plan; and the long-range where groups of lessons or courses are developed, ideally by a team of instructional designers and other stakeholders. They emphasise the systems approach beginning with an analysis of needs and ending with evaluation. Gagné et al. (1992) also provided nine events of instruction (in the context of computer-based instruction) that employ a largely behaviourist approach (for example the words stimulate and stimuli feature as well as the phrase “elicit performance”). It is a highly-structured model for instructional design at the level of the lesson.

It is not practical to catalogue all ISD models given how numerous they are (Gustafson and Branch 1997). Instead, two of the more widely used are described: ADDIE is a well-established and widely-used model, whereas SAM is an emerging model based on modern agile software development methodologies.

2.5.5.8.1 ADDIE

ADDIE (an acronym for analysis, design, development, implementation and evaluation) is one such systems approach to instructional design. Rather than being a specific model attributable to any particular person or persons, ADDIE is an umbrella term for a general approach to instructional design (Molenda 2003). ADDIE is still probably the most widely used model of instructional systems design (Rothwell et al. 2015, p.121). It is also a framework upon which many other models of instructional design have been based (Gustafson and Branch 2002).

Though ADDIE was often represented graphically as a sequence from analysis through evaluation, it is now usually a more iterative process with continual evaluation, revision and backtracking (as illustrated by Figure 2.12). Peterson (2003) represents ADDIE graphically (Figure 1 in the article) as a more linear process with the evaluation step looping back around to the analysis step, but goes on to explain that evaluation can take place during the development phase as a formative evaluation with the aid of students and the instructor, and also at the end of the delivery of the course or program as “a summative evaluation for instructional improvement”.

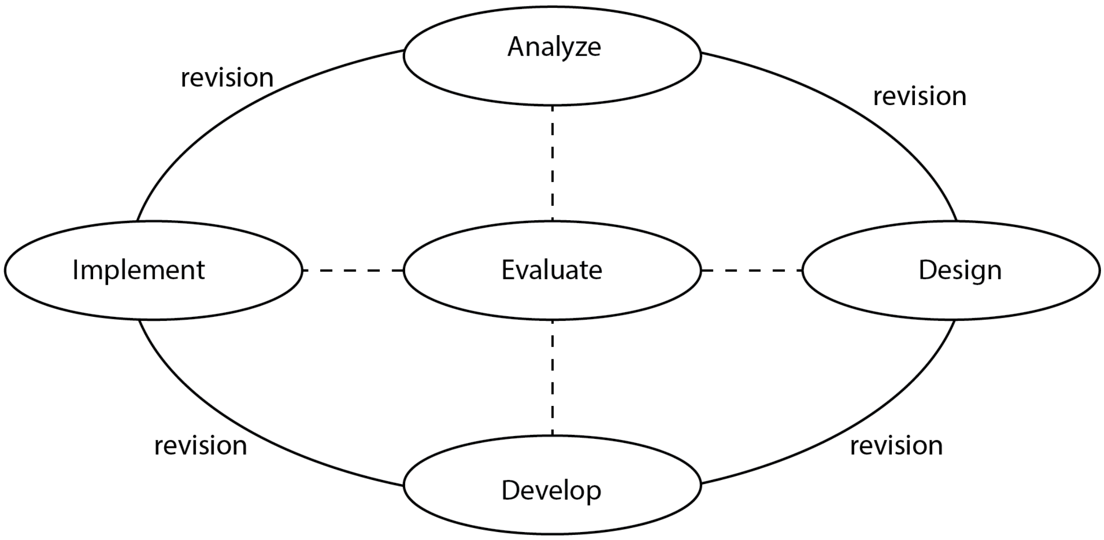


Figure 2.12: The ADDIE Model of Instructional Design (image reproduced from Gustafson and Branch (2002))

Evaluation can be considered the hub to which the other stages of the ADDIE model are connected. It is intended to be a continuous process conducted during and after each stage.

2.5.5.8.2 SAM

The Successive Approximation Model (SAM) (Allen 2012) is heavily influenced by agile software development and agile project management techniques. While ADDIE has been updated to become a more iterative model, where it is possible to prototype frequently and evaluate prototypes frequently, SAM is more explicit in its approach.

One issue with ADDIE that SAM attempts to resolve is how differently ADDIE might be employed from institution to institution. ADDIE is a systematic approach, but it is not tightly defined. SAM is tightly defined and has two levels of complexity: SAM1 for simpler instructional design projects and SAM2 for larger scale projects. SAM2 includes, for example, a *Savvy Start*, which is typically a one-day event where key stakeholders get together to define the broad outline of an instructional design project and begin brainstorming ideas before sketching out what a rough initial prototype might be.

It takes the classical agile approach of doing *just enough design initially* (the so-called JEDI principle), leaving implementation until the *last responsible moment* (LRM). In other words, avoid *big design up-front* (BDUF) because design evolves over time and implementing requirements too early can lead to expensive changes later if the requirements subsequently change. Agile principles are discussed in more depth in Section 2.6.

2.5.6 What is Learning Anyway (and What Should it Look Like)?

The section on teaching and learning has cast its net wide, examining the theories underpinning learning, attempts to cater for the individuality of learners, how the learner is increasingly put front and centre in teaching, how learners takes charge of their learning, and how to structure teaching and learning. How can such a wide variety of perspectives and approaches to learning be summed up in just one or two paragraphs? The author here makes an attempt to do so from the author's perspective (or philosophical viewpoint having been involved in teaching and learning as a professional for many years; something of a personal narrative).

Learning is not just a hidden cognitive process with inputs and outputs. An educator obviously has an important role to play, but is primarily a facilitator (and at times a curator), creating the conditions for the learner to construct their own knowledge in their own way. In an ideal world, free from managers and quality control bodies, or the jobs market and curriculum vitae, learning would primarily be emergent with only the very faintest of constraints (such as basic fundamentals) on what is to be learned. One might say that the ideal only intended learning outcome for a module of learning should be that it makes the learner learn something of value to them, firstly, and to wider society, secondly.

The author is persuaded by the constructivist position that learning should be situated (leading to membership of a community of practice), and that it should also encourage open inquiry. Particularly persuasive were Lave's community of practice and Brown et al.'s cognitive apprenticeship, both of which promote learning in authentic real world environments. Students cannot be hand-held from one year of their studies to the next—autonomy should be encouraged to let students take charge, to plan, to set goals. Learning should be inclusive. Learning should be engaging and be of relevance to the learner. Where possible, it should be fun.

2.6 Agile Software Development and its Relationship to DGBL

The agile approach to software development, and by extension instructional design, was touched upon when discussing the SAM model in Section 2.5.5.8.2. It is important to delve deeper into the principles and practices of agile software development because the primary output when developing a DGBL solution is software. However, the majority of the principles and practices apply to the development of any solution, including more traditional instructional materials.

In 2001, a group of leading practitioners in the field of software development came together to form the Agile Alliance. They began working on a set of values that ultimately became known as *The Manifesto of the Agile Alliance* (Agile Alliance 2001). There are twelve principles behind the manifesto. Robert C. Martin lists and discusses the principles in *Agile Software Development: Principles, Patterns, and Practices* (2011).

Martin Fowler, one of the signatories of the Agile Manifesto, contrasts agile development with traditional software development, which is based on rigid plans:

> *Agile* Development
> — is *adaptive* rather than predictive
> — is *people-oriented* rather than process-oriented (Fowler n.d.)

What Fowler is saying is that the designer does not try to predict too much up front, and instead adapts the design as more is learned. He is also saying that the person (in the case of DGBL, the learner) is integral to the process.

Agile approaches to software development have become mainstream with even the largest of organizations adopting it (Brhel et al. 2015). Agile development has also been embraced widely by game developers (Schell 2015, p.98). When adopting the agile principles for the development of DGBL solutions, some substitutions are necessary, such as replacing *customer* with *learner*. Some of the principles, with those substitutions made, are discussed here in relation to the development of DGBL solutions.

2.6.1 Early and Continuous Delivery

> Our highest priority is to satisfy [learners] through early and continuous delivery of [a DGBL solution].

This principle requires some additional context. It is generally not practical to pilot early prototypes on the full cohort of students, so a representative sample needs to be chosen. Martin (2011) cites a *MIT Sloan Management Review* analysis of software development practices that led to higher quality products. There was a negative correlation between the amount of initial functionality delivered and the quality of the final software delivered. Perhaps counter-intuitively, the less implementation done early, the better the results in the long run. A positive correlation found was between frequency of delivery of working software iterations and the quality of the final product.

Therefore, as early as possible a rough working prototype is tested, followed by frequent revisions based on feedback from stakeholders (for example, learners and educators).

The scrum project management framework is the embodiment of the agile manifesto in practice. Jeff Sutherland, co-creator of scrum, compares the framework to “evolutionary, adaptive, and self-correcting systems” (2015). Scrum consists of sprints, usually two weeks to one month in duration, where a pre-planned set of *stories* (individual requirements) are locked down and worked on by a team for that duration. The end goal of a sprint is to produce a working prototype (the final sprint will produce the final product). More detail on the scrum project management framework is also available in *Agile Project Management with Scrum* written by the other co-creator, Ken Schwaber (2004).

Schell (2015) provides several tips for agile game development. These include (explanations are summarised and modified for the DGBL context):

Answer a question: Develop prototypes to answer one or more questions: for example, is the game successful in teaching one or more learning outcomes? Do players get bored or find it too challenging?

Forget quality + Don't get attached: "Quick and dirty" is the mantra. If the question being answered by a prototype is about whether learning is transmitted successfully, then how graphically pleasing the game is is not important. Because change should be embraced and planned for, polish, for example, should be left until the LRM (last responsible moment). Prototypes are often disposable—if the main question was not answered, for example.

It doesn't have to be digital: Paper prototyping can be very effective and cheap in terms of time and effort. Ideas can be tested quickly. A scissors, glue and other art supplies can be used to construct paper (or card-based) prototypes that allow for game mechanics, dynamics and aesthetics to be tested before there is a significant investment in a digital version.

2.6.2 Embracing Change

> Welcome changing requirements, even late in development. Agile processes harness change for [improved learner outcomes].

An agile process can help overcome a fear of change because the impact of change is minimal. A waterfall approach (that is, step-by-step with larger chunks of work in between testing) results in heightened anxiety with respect to late changes. With an agile approach, change is seen as a good thing because changes are usually an indication of improvement (more is being learned about what the learner needs and how to deliver on learning objectives).

2.6.3 Measuring Progress

> [A working DGBL solution] is the primary measure of progress.

Progress is measured by how much the DGBL solution is meeting the learner's needs. For example, a game might include a number of high-level learning outcomes broken down into smaller, more granular learning outcomes. When taking this perspective on the measurement of progress, one cannot point to underlying game engine code or documentation or the phase of development reached, none of which is of concern to learners. The DGBL solution is 50% complete when 50% of the learning objectives are being delivered on by the solution.

2.6.4 Retrospective Reflection

> At regular intervals, the team reflects on how to become more effective, then tunes and adjusts its behaviour accordingly.

This is a process and behaviour-related principle. Whatever development process is chosen or devised, whether it is the AMDGBL or not, it needs to be revisited periodically. Questions could be asked, such as: are the models or frameworks chosen working? If the LM-GM model is used to evaluate the learning taking place, is it effective at doing so? Is the size and frequency of prototyping appropriate?

Jeff Sutherland writes that teams should "inspect and adapt", which he explains means not just regularly inspecting what is being produced and if it is what the customer wants, but also how the work is being done to see if there are improvements that will do things better or faster (Sutherland 2015, p.11). In scrum terminology, when done formally at the end of each sprint, it is called a *retrospective*.

2.7 Universal Design for Learning

2.7.1 Universal Design

There has been an imperative for more than half a century to provide equal access for all. For example, the US Supreme Court's 1954 decision in the *Brown vs. Board of Education* case that stated that "separate is not equal" and the realization in Japan that their population was the fastest-ageing in the world. Universal design (UD) has its roots in an area of architectural design and the Americans with Disabilities Act of 1990, which required, for example, all public buildings to be accessible to people with disabilities (Thompson 2015, Lieberman 2017). More recently, the United Nations Convention on the Rights of Persons with Disabilities (CORD) included the definition that "'Universal design' means the design of products, environments, programmes and services to be usable by all people, to the greatest extent possible, without the need for adaptation or specialized design" (Preiser and Smith 2010).

In 1997, the Center for Universal Design at North Carolina State University published seven principles of universal design (Follette Story 2010):

1. Equitable Use
2. Flexibility in Use
3. Simple and Intuitive Use
4. Perceptible Information
5. Tolerance for Error
6. Low Physical Effort
7. Size and Space for Approach and Use

There is a large amount of literature on the application of UD in, for example, the built environment and product development (Mace et al. 2015, Demirbilek and Demirkan 2004, Meyer and Rose 2000). In an educational context, the seven principles have underpinned the universal design of instruction (UDI) framework (Burgstahler 2009). The framework provides a set of eight categories of instruction that follow the principles of universal design, each with a goal statement and examples. The following lists each category with a goal statement from the UDI document (for the examples, refer to the document itself):

Class climate Adopt practices that reflect high values with respect to both diversity and inclusiveness.

Interaction Encourage regular and effective interactions between students and the instructor and ensure that communication methods are accessible to all participants.

Physical environments and products Ensure that facilities, activities, materials, and equipment are physically accessible to and usable by all students, and that all potential student characteristics are addressed in safety considerations.

Delivery methods Use multiple, accessible instructional methods that are accessible to all learners.

Information resources and technology Ensure that course materials, notes, and other information resources are engaging, flexible, and accessible for all students.

Feedback Provide specific feedback on a regular basis.

Assessment Regularly assess student progress using multiple accessible methods and tools, and adjust instruction accordingly.

Accommodation Plan for accommodations for students whose needs are not met by the instructional design.

UDI is a set of high-level goals and contrasts with the greater level of detail in the Universal Design for Learning (UDL) framework, which has 31 checkpoints and a very large number of concrete examples.

2.7.2 The UDL Framework

Universal Design for Learning (UDL) is a framework for the design and delivery of mainstream education that caters for learners from the widest possible set of backgrounds and abilities. While much of the focus of universal design has focused on leveraging technology to increase access, the implications of universal design for learning go much further (Meyer et al. 2016). Gargiulo and Metcalf (2016) provides a categorisation of students in addition to those with disabilities: students who are gifted and talented, students who are culturally and linguistically diverse, and students who are at risk. The gifted and talented must be supported to maximise their abilities, the culturally and linguistically diverse must be respected, and the at risk may or may not be challenging due to the difficult circumstances they face outside the learning environment. The UDL framework offers a way to reach those diverse groups of learners.

UDL is increasingly being adopted by universities, but not broadly integrated into higher education policy (Izzo et al. 2010). The UDL framework provides for a multiplicity of representation, expression and engagement, as set out by the Center for Applied Special Technology (CAST 2018). While often associated with making learning accessible to people with disabilities, the framework is for all learners. It is theoretically based, with reference to learning theories such as Kolb's experiential learning cycle and Vygotsky's zone of proximal development, as well as other literature on metacognition, self-regulation, and more (Gargiulo and Metcalf 2016).

Figure 2.13: The UDL Framework High-Level Diagram

The framework is presented as a three-by-three grid (Figure 2.13) of high-level guidelines, which are broken down into thirty-one checkpoints. Each of the thirty-one numbered checkpoints, which are accompanied by examples, would be too numerous to detail here in the way the high-level guidelines are. The columns organise the checkpoints under multiple means of *engagement* (the why of learning), *representation* (the what of learning) and *action and expression* (the how of learning). The guidelines, with highlighted text from CAST (2018), are:

Recruiting Interest Information that is not attended to, that does not engage learners' cognition, is in fact inaccessible.

Sustaining Effort & Persistence ... When motivated to do so, many learners can regulate their attention and affect in order to sustain the effort and concentration that such learning will require. However, learners differ considerably in their ability to self-regulate in this way.

Self Regulation ... The ability to self-regulate—to strategically modulate one's emotional reactions or states in order to be more effective at coping and engaging with the environment—is a critical aspect of human development. ... Those teachers and settings that address self-regulation explicitly will be most successful in applying the UDL principles through modeling and prompting in a variety of methods.

Perception ... it is important to ensure that key information is equally perceptible to all learners by: 1) providing the same information through different modalities ... 2) providing information in a format that will allow for adjustability by the user.

Language & Symbols ... inequalities arise when information is presented to all learners through a single form of representation. ... ensure that alternative representations are provided not only for accessibility, but for clarity and comprehensibility across all learners.

Comprehension ... Constructing useable knowledge, knowledge that is accessible for future decision-making, depends not upon merely perceiving information, but upon active "information processing skills" ... Proper design and presentation of information ... can provide the scaffolds necessary to ensure that all learners have access to knowledge.

Physical Action ... It is important to provide materials with which all learners can interact. Properly designed curricular materials provide a seamless interface with common assistive technologies.

Expression & Communication ... It is important to provide alternative modalities for expression, both to level the playing field among learners and to allow the learner to appropriately (or easily) express knowledge, ideas and concepts in the learning environment.

To illustrate how the framework is accessed (and how accessible it is), the *Sustaining Effort & Persistence* high-level guideline is examined here. The guideline is given the number 8 and contains four checkpoints:

8.1 Heighten salience of goals and objectives

8.2 Vary demands and resources to optimize challenge

8.3 Foster collaboration and community

8.4 Increase mastery-oriented feedback

It is then possible to further drill down into each checkpoint to get an explanation and examples. For example, checkpoint 8.1 provides the following examples of how to heighten the salience of goals and objectives:

- Prompt or require learners to explicitly formulate or restate goal
- Display the goal in multiple ways
- Encourage division of long-term goals into short-term objectives
- Demonstrate the use of hand-held or computer-based scheduling tools
- Use prompts or scaffolds for visualizing desired outcome
- Engage learners in assessment discussions of what constitutes excellence and generate relevant examples that connect to their cultural background and interests

Since the goal of UDL is to make learning accessible to, and empowering for, the widest range of learners, this means catering for a wide range of learning preferences. This was discussed in 2.5.2 where an index of learning preferences from Winebrenner (2009) was provided. Table 2.18 shows how UDL can be used as a guide to come up with examples of learning tools that would suit the different preferences (examples are from Gargiulo and Metcalf 2016, p.42).

There is a growing amount of literature on the practical application of UDL. An example is Dean et al. (2017) where UDL was used to design an environment for very large class sizes (up to more than 600 marketing students) for the benefit of all students. To assist students with learning disabilities, Marino et al. (2014) supplemented traditional teaching and learning techniques with video games using UDL to guide the integration of the new technology, leading to an improvement in engagement.

Table 2.18: Learning Preferences from Winebrenner (2009)

Type of Learner	**Learning Tools**
Visual/Verbal	Lectures with overhead
	Textbooks
	Class notes
	Graphic Organizers
Tactile/Kinaesthetic	Modelling/Demonstration teaching
	Field experiences (Community-Based Instruction)
Visual/Nonverbal	Use of visual aids (video, maps, charts Visual Display Models, pictures, pictograms)
Auditory/Verbal	Group discussions
	Audiotapes

2.7.3 Universal Design and DGBL

During the evaluation of the game and platform in Section 4.5, it is shown how a game can be formatively evaluated using the UDL checkpoints. That section goes into more detail on some of those checkpoints than the high-level overview presented in this section. To go into detail on all 31 checkpoints would require a significant number of paragraphs. However, the following sub-sections address accessibility of DGBL for people with disabilities.

2.7.3.1 UD, DGBL, and People with Disabilities

There are two categories of game discussed in this section: games to help people cope with or overcome a disability usually with health games or exergames (Section 2.7.3.2), and general-purpose games that cater for disabilities to make them more inclusive (2.7.3.3).

2.7.3.2 UD and Games for Disabilities

An example of a game that helps players better cope with a disability is *FroggyBobby* (Caro et al. 2017). It is an exergame for children with motor coordination problems (including autism, dyspraxia and hyperactivity). The authors reviewed existing literature and products and were unable to find a game with an appropriate level of complexity in terms of game mechanics and cognitive load for children.

It is debatable whether it can be said that *FroggyBobby* has been designed universally, in the sense that is meant by the UDL framework, for example. The game was specifically designed for a narrow population: children with motor coordination problems. Prior to designing and building the game, the authors embarked on a qualitative study to try to gain a better understanding of the needs of children with this type of disability. They solved the issues of game mechanics and cognitive load—using a Microsoft Kinect, arm movements and a simple mechanic of making a frog catch flies—to make the game accessible to a great number of children with motor coordination problems, so it could be said that the game was designed to be universal to that population. They also included features that would have been universal to a larger population, had the game been aimed at them, such as personalised frog avatars.

Another example is *Pico's Adventure* (Malinverni et al. 2017), which took a *participatory design* approach to the game, involving children with autism. A number of sessions with four children aged nine to ten were carried out to "identify their preferences, interests, and motivations". The target age of the game was four to six, but it was decided that children of age nine or ten were more appropriate for participatory design activities. The contributions of the children were then combined with those of autism experts. Ultimately the game was designed with rewards that coincided with the children's interests and contained a narrative that engaged children with autism.

It does not automatically follow that a DGBL solution designed specifically for a disability is a universally-designed DGBL solution. However, games for disabilities can be designed in a way that is universal for the intended population.

2.7.3.3 UD and Games that Cater for Disabilities

Catering for people with disabilities can take two approaches: specific and non-specific. A specific approach would mean identifying a disability to cater for and then carefully designing the game and any input devices for that disability. The non-specific approach tries to be broad and flexible—controls are kept simple and choices are added, such as speech, subtitles, language translations, colour schemes for the colour blind, and so on. Both approaches will concentrate on how the game itself is designed and coded and the hardware required to play the game, both of which can be altered to cater for disability.

2.7.3.4 UD and Game Controls

There are several approaches to a game's controls from a UD perspective. The first is to employ widely-used controllers, such as joysticks, gamepads, or mouse and keyboard, and then design the game's control scheme to be as accessible as possible. To improve accessibility, a minimal approach to the control scheme should be taken—as the *FroggyBobby* example showed, overly-complex controls or mechanics can make a game inaccessible to some.

The second approach to game controls is to support specialised controllers that have been designed for players with disabilities. This includes the disability-friendly XBOX controller, which allows the player to use feet, elbows or hands, even where fingers might be missing (Stuart 2018). Another example is the "camera mouse", which has been tested on people with cerebral palsy and traumatic brain injury (Betke et al. 2002). While these controllers allow existing control schemes to be used, the principle of minimal control schemes still applies.

VR introduces a third approach. A HMD can also be a controller. Internal and external sensors allow head position to be tracked. A dot can be superimposed on the player's view. As the player's head moves, the player can use the dot to aim at objects. Time can be used to determine if an object is to be interacted with—for example, a player might stare at an object for five seconds to select it. Through careful design, it is possible to implement a control scheme based only on this gaze mechanic in most DGBL solutions. For example, a menu system could be placed on a wall and the menu could be navigated by gazing at options for a predetermined amount of time.

The final approaches discussed here are more experimental: eye tracking and brain-computer interfaces (BCI). Both approaches could be used for cases where movement is extremely limited or unstable, including an inability for the neck to support a VR headset or where neurological disorders make the VR gaze mechanic unstable. While eye tracking is often used in studies of behaviour, such as the way users interact with web pages or games, it can also be used as a way of controlling games. Smith and Graham (2006) use eye tracking to improve immersion in a game. Belkacem et al. (2015) discuss the use of both eye tracking and BCI for game control.

2.8 Use of Data to Assist Learners and Educators

This section explores two areas that are related to each other through data, learning analytics and personalised adaptive learning.

2.8.1 Learning Analytics

Learning analytics (LA) is an emerging and growing field of study of increasing interest not just to individual educators and researchers but also to educational institutions, governments, industry and the public (Lockyer et al. 2013, Greller and Drachsler 2012). LA can be used to improve student retention, learning outcomes, engagement, relevance of learning content, and to identify where learning supports can be targeted (Siemens 2013). It can provide automated feedback (Sonnenberg and Bannert 2015) and can influence the design and evaluation of a curriculum by seeing what works (Rienties and Toetenel 2016, Greller and Drachsler 2012).

A widely-used definition of LA was provided at the 1st International Conference on Learning Analytics[10]:

> Learning analytics is the measurement, collection, analysis, and reporting of data about learners and their contexts, for the purposes of understanding and optimizing learning and the environments in which it occurs.

Learning analytics, while being grounded in the field of data science, also borrows from psychology (e.g. metacognition), business analytics (e.g. dashboards with actionable items) and the science of learning (Lodge and Corrin 2017).

However, LA is not without criticism. "Managerial faddism" sees problems as being solvable through better management and in the case of LA, this means a

[10] https://tekri.athabascau.ca/analytics

technology being borrowed from another context without full consideration of its limitations (Beer et al. 2014). One of the limitations of the technology is the focus on behavioural data, which cannot give a holistic view of learning (Lodge and Corrin 2017).

Chatti et al. (2012) offer a reference model for LA based on the what (data environments), how (techniques, such as statistics, visualizations and social network analysis), who (stakeholders, such as learners, educators, researchers and institutions) and why (including monitoring, mentoring, prediction, adaptation, personalisation and reflection). Greller and Drachsler (2012) offer an alternative framework for LA featuring stakeholders, objectives, data, instruments, external limitations and internal limitations. It addresses some aspects of LA that Chatti et al. (2012) does not, such as privacy, ethics and capability. Either model / framework can be used to determine whether the data available is being used in the widest way possible.

The use of analytics in the video games industry is widespread, often used as a way to evaluate player experience or determine if a game is balanced (El-Nasr et al. 2013). The Unity game engine, for example, includes analytics as standard[11]. *Kerbal Space Program* is a game that uses Unity Analytics and among the uses of captured gameplay data is to “rebalance missions if we see a low completion rate and think it is too difficult”[12].

The tracking of data in serious games is quite infrequent: Serrano-Laguna et al. (2017) examined 120 research papers where serious games were evaluated and of those only 14 used data tracking and only a small proportion of those were fine-grained in the way the LA solution for this research was developed. The data gathered often consisted of simple data, such as whether a game had been completed and thus was not directly related to specific learning outcomes. Others used fairly crude mechanisms such as points and coins to determine if learning had taken place.

The following section explores learning analytics dashboards, which are one manifestation of learning analytics visible to end users (as opposed to other automated uses of learning analytics, such as in adaptive learning).

[11] https://unity.com/solutions/analytics
[12] See the community announcement on Steam: http://bit.ly/2O1HZif

2.8.1.1 Learning Analytics Dashboards

Yigitbasioglu and Velcu (2012) define a dashboard as a:

> data driven support system ... [that is] expected to improve decision making by amplifying cognition and capitalizing on human perceptual capabilities.

Dashboards have been a feature in business since the 1980s (when executive information systems were developed) and from a business standpoint provide “timely information and insights ... to improve decisions, optimize processes and plans, and work proactively” (Eckerson 2010, p.4-5). According to Eckerson, a performance dashboard allows business people to “monitor critical business processes”, “analyze the root cause of problems” and “manage people and processes to improve decisions”. While the focus of performance dashboards is very much on business processes, strategies and objectives, it does offer individuals benefits in terms of increased visibility and empowerment, and delivers “actionable information” (according to Eckerson, when data is delivered in a “timely fashion”, users can take action before it is too late to solve problems).

A review of the limited amount (at the time) of literature on dashboards by Yigitbasioglu and Velcu (2012) found that dashboards can solve problems like presentation format and information overload when certain design principles are followed, such as providing drill-down features. They also recommended that they include flexibility, such as providing choice of presentation formats (an example would be allowing a switch between a tabular and a chart format).

A number of recent research papers have focused on how learning analytics is made available to educators and students via learning analytics dashboard (LAD) applications (Verbert et al. 2013) and how effective LADs are (Roberts et al. 2017, Kim, Jo and Park 2016). LADs represent a continuation of a movement towards more open learning environments (Verbert et al. 2014).

Verbert et al. (2013) distinguish four stages in the use of learning analytics applications (see Figure 2.14). While the presentation of data (such as through tabulations or visualizations) raises *awareness*, the data presented requires *reflection* with users asking questions about the relevance of the data. This is followed by *sensemaking*, where the data has been interpreted and insights gained, leading to an *impact*, such as behavioural change or new meaning.

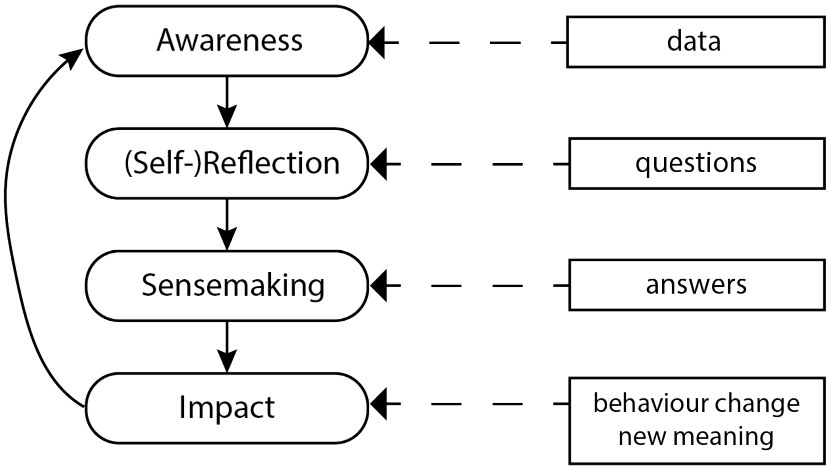


Figure 2.14: Learning Analytics Process Model (LAPM), reproduced from Verbert et al. (2013, Figure 1).

Verbert et al. (2014) provide a categorisation of LADs into three broad categories that support:

1. traditional face-to-face lectures;
2. face-to-face group work;
3. the four stages of the LAPM model.

It is in the third sense (that of the LAPM model) that this thesis focuses on. This is consistent with a finding that when learners are given regular feedback (which a dashboard can), their learning is deeper (Erhel and Jamet 2013).

Roberts et al. (2017) found that the majority of students were positive about many features that could be placed in a dashboard, such as a comparison of performance to peers—as long as it was anonymous and was implemented in a way to minimize the demotivating effect of poor performance, such as providing links to supports. The same conclusion was reached by Kim, Jo and Park (2016) who found that LADs should be implemented in a way that motivates learners and supports those learners who are struggling. The authors found some correlation between students who used a dashboard and improved academic achievement.

Only one platform similar to the AMDGBL platform was discovered in the literature: REAPER / RAGE Analytics. Rather than detail that platform here, it is instead compared to the AMDGBL platform in Section 4.3. Another platform of note is OneUp (Dichev et al. 2018), which is a gamification-driven learning analytics platform. That platform, like most gamification systems, rewards learners with points and badges for learning achievements, such as completed learning and challenges. Because it is not embedded in a game engine, such as Unreal Engine 4, it cannot provide the same level of fine-grained detail that allows for visualizations of exercise performance, such as the ones presented in Section 4.3.2 that can visualize every possible action taken by a learner. OneUp is similar to the *gameful design* approach discussed in Aguilar et al. (2018), which references a platform called *GradeCraft*[13] that the researchers have been using for several years. *Gradecraft* is a learning management system that supports "gameful instruction".

2.8.1.2 Automation

LA can be more than just reporting and can progress from data to reporting (such as tables and charts) to analytics (e.g. insights) to action (e.g. recommender engines to recommend new content based on prior learning, the related preferences of other learners, or a combination) (Chatti et al. 2012). A recommender engine is something automated, responding in real-time or periodically (such as an email alert). Another automated use of data is for personalised adaptive learning, discussed in the next section.

2.8.2 AI and Personalised Adaptive Learning

An area that is related to LA, because of its reliance on data (Chatti et al. 2012, consider it to be part of LA), is personalised adaptive learning (PAL). PAL is usually context-based, examining learner profiles, such as location, specified learning preferences or goals, and other human factors (Chen 2008, Hwang et al. 2013).

Hwang et al. (2013) advise the consideration of learning preferences when devising PAL solutions, citing examples from other research, such as the difficulty some students face when transitioning from 2D representations to 3D. A PAL in this scenario would recognise a learner's preference and serve appropriate learning objects (a 2D model as opposed to a 3D model). Chen (2008) uses a genetic algorithm that uses learner pre-test data to make

[13] http://www.gradecraft.com

decisions about sequencing of topics based on learning object difficulty and relatedness.

Machine learning (ML), which is a subset of artificial intelligence (AI), is perhaps the most exciting emerging means of implementing PAL. It has made searching the literature for human learning concepts, such as deep learning and reinforcement learning more difficult as machine learning equivalents of the same name have popped up in recent years.

ML is defined as "a set of mathematical techniques, implemented on computer systems, that enables a process of information mining, pattern discovery, and drawing inferences from data" (Chio and Freeman 2018). The area of ML is far too vast to do justice to in this section other than with a very brief overview. In some sense this is unfortunate, because the potential for the use of ML with learner interaction data is immense; however, the use of ML in human learning is a topic worthy of its own thesis and it is brought to the reader's attention so as to be aware that because learner interaction data plays an important role in the AMDGBL, it is worth considering the use of ML when designing and building a game. The significance of ML to DGBL is discussed further in Section 6.4 concerning future work beyond this thesis.

ML research is broadly organised around three areas (Michalski et al. 2014, p.3-4):

- Task-oriented studies
- Cognitive simulation
- Theoretical analysis

Cognitive simulation is concerned with simulated human learning processes. This, of course, is not the same as simulating teaching. The task-oriented approach is an "engineering approach" designed to improve task performance (Michalski et al. 2014)—one could consider teaching or guiding to be a task. However, as Michalski et al. note, one can lead to the other; for example, an algorithm can learn to be a better teacher. An algorithm could do this in a number of ways, such as analysing learner performance data and recognising patterns (from observation of behaviour through data or from human observation and labelling of data) that occur in high-performing or low-performing students and assisting students to learn like high performers (ideally with reference to learner context, such as specified preference).

The two most widely-used type of ML algorithm are (with summaries based on Michalski et al. 2014, Chio and Freeman 2018):

Supervised Previously-captured events can be analysed to infer the probability (in other words, predict using a Bayesian approach) of future events occurring. The algorithm is trained with labelled data. An example would be learner interaction data that was labelled with ‘trial-and-error’ when that type of behaviour was observed by a human. Many supervised algorithms exist, such as linear regression, decision tree, neural networks, k-nearest neighbour, and naive bayes.

Unsupervised Unlike supervised learning, the data is not labelled. It is a more complex approach that can be used to solve problems that are highly dimensional, thus being impossible for human observation to cope with. Alternatively, it can be used where a human could observe but there are too many events to manually observe. The approach can draw abstractions from data to reapply to new data. Unsupervised algorithms include k-means clustering and association rules.

The use of AI in general offers many possibilities. The concept of cognitive apprenticeship was briefly touched upon in Section 2.5.1.3. A related concept is that of guided participation (Rogoff 1990), where an experienced person helps a less experience person to develop a competency. AI gives the designer the ability to facilitate artificially-intelligent guided participation, for example through a ‘bot’ (in a game often represented by what is known as a non-player character, or NPC) that employs natural language processing (which is an area of research that looks at how AI can communicate with us using language that appears natural as discussed in Chowdhury 2003) in conjunction with adaptive learning (based on a history of learner data and the patterns that emerge). Perhaps the ultimate goal would be for AI to assume the role of the master and pass on procedural knowledge to the apprentice; the AI would need to be trained or to train itself on this knowledge.

2.9 Research Questions

The Adaptive Model for Digital Game-based Learning (AMDGBL) is intended to be an overarching model for the development of effective learning games that incorporates several theories, models and frameworks. Two of the core features of the AMDGBL and its associated learning analytics platform are that:

1. it should assist *DGBL developers* iteratively develop high-quality, universally-designed learning games;
2. it should help *learners* be more autonomous and able to perform executive functions.

The choice of game medium was driven by the second feature and this led to the choice of VR, because it was perceived as affording a high degree of freedom in terms of locomotion, physical interactivity and immersion. Therefore, it was hypothesized that VR would allow for a higher degree of autonomy than other games media.

The following research questions were devised, having completed a comprehensive literature review, to investigate the key features of the model, learning game and learning analytics platform. Each is listed with an explanation as to its significance and value.

RQ1 *Will the AMDGBL allow for iterative improvement of the graph game prototype?*

The development of DGBL solutions is the development of a particular kind of software. The prevailing methodology for software development, and increasingly instructional materials, is an iterative or agile one, consisting of frequent prototyping and evaluation involving key stakeholders to progressively improve the solution. The AMDGBL should facilitate this approach and provide the necessary tools for formative and summative evaluation.

RQ2 *Will the use of the AMDGBL lead to an effective DGBL solution?*

Ultimately, the learning game developed must be effective from several perspectives, including learning outcomes, motivation to learn, and efficiency with respect to other methods of learning.

RQ3 *Will the inclusion of UDL in the model lead to a game that is more universally designed?*

The ideal scenario is a difficult one to deliver on: that the learning game developed can be used easily and effectively by all learners. However, it goes further than just accessibility. The UDL framework consists of 31 checkpoints, each addressing learning from different standpoints, including self-regulation, multiple means of representation, executive functions, and more. It should be possible to evaluate formatively and summatively whether a learning game succeeds from a UDL perspective and identify areas of improvement.

RQ4 *Will a learning analytics dashboard help learners with executive functions, such as assessing their performance, setting goals and planning?*

The inclusion of a web-based dashboard with actionable information accessible to learners should help them with executive functions, such as employing metacognition to understand how they are doing as an individual and in comparison to their peers, as well as goal setting and planning the next course of action, whether that is a progression forward or taking a step back to address missing knowledge or skills.

RQ5 *Will the immersive and open nature of the VR environment foster learner autonomy?*

The high degree of freedom (of bodily movement) facilitated by the sense of presence and proprioception that VR gives, should allow learners find their own strategies for learning, cater for many learning preferences and improve cognition due to bodily-kinaesthetic learning. There should be evidence, therefore, of a range of strategies employed by learners when attempting to solve exercises in an immersive environment that allows learners freedom of movement and the ability to interact in various ways with objects.

2.10 Research Objectives

Based on the research questions posed, the following objectives should help answer them.

O1 Investigate ways in which DGBL solutions can be evaluated so that as each iteration produces a prototype, the prototype can be formatively evaluated in a timely manner to allow for improvement of the prototype during the next iteration.

O2 Design and develop a learning analytics platform incorporating an API and web-based dashboard.

O3 Design and develop an effective, universally-designed VR-based DGBL solution using the AMDGBL.

O4 Evaluate how well O2 contributed to the successful completion of O3 and also helped learners to perform executive functions.

O5 Evaluate the opinions of DGBL practitioners on the AMDGBL approach to the development of effective learning games.

How O1 was achieved is described in Chapter 3. In Chapter 4, Section 4.3 addresses the design and development of the learning analytics platform (O2), while Section 4.4 details the design and development of the learning game (O3). Both O4 and O5 are addressed by the studies of learners and practitioners in Chapter 5.

2.11 Chapter Conclusion

This chapter carried out a wide-ranging survey of the literature on areas related to the research questions and objectives. This included the theories, lenses, models, frameworks, processes, and so on, that underpin the Adaptive Model for Digital Game Based Learning. This covered a wide range of areas, starting with a review of why we play and how games are structured. This lead into a comprehensive review of digital game-based learning, which began with a definition of serious games / DGBL and a discussion about the effectiveness of DGBL. What was clear from that discussion was that effective learning games need to be both entertaining and well-integrated in terms of learning. Therefore, how to make games engaging was explored and the models for embedding learning in DGBL were examined. The review of DGBL concluded with some exemplars and a discussion of diversity in games.

This chapter continued with a look at virtual reality and its affordances for certain types of learning, such as bodily-kinaesthetic. To counter the positives, some of the negatives, such as VR motion sickness were examined, and lessons for designing VR-based solutions were uncovered. The chapter then moved on to the numerous theories of teaching and learning. Pedagogy is an enormous area of study and entire theses can be dedicated to the subject, so this section attempted to review those areas of the literature that were of most relevance to the research at hand. This included the historical underpinnings of learning with a brief discussion of empiricism and rationalism before the dominant theories of the 20th century were covered: behaviourism, cognitivism and constructivism. To acknowledge the increasing role that technology and the internet are playing, connectivism was also briefly discussed. Increasingly, the learner has been put at the centre of teaching and learning and so the topics of learner preference, student-centred learning and learner autonomy were discussed. The teaching and learning section concluded with a review of theories, models and frameworks that help educators and instructional designers develop effective instruction, such as taxonomies of learning, Bruner's spiral curriculum, Kolb's experiential learning cycle and Vygotsky's zone of proximal development. Finally in the section, instructional systems design models were examined (Gagné's nine-events, ADDIE and SAM).

The literature review continued with agile software development. It was clear from the review of instructional design models that iteration was key to successful instructional design. The agile approach was discussed with reference to agile project management frameworks such as Scrum. The principles of agile methodologies, such as frequent prototyping with the inclusion of stakeholders, and continuous integration, were explored.

The review then moved on to one of the core facets of the AMDGBL, universal design. UD was first put in perspective with the seven principles, examples of UD in practice and the UDI framework for instruction. The major part of the section explored the UDL framework and how it supports learners from many perspectives, including accessibility, self-regulation, autonomy, and much more. A discussion of how UD could address DGBL accessibility issues showed practical ways of catering for people with disabilities.

The chapter continued with a discussion of how data can be used to help learners, educators and other stakeholders. The major part of this was learning analytics, with a particular focus on learning analytics dashboards that provide learners with actionable information and help them with goal setting, planning and other executive functions. The automation of learning analytics lead into how AI, and ML in particular, have great potential in assisting learners to learn in a digital environment.

With the review complete, it was then possible to pose the research questions and outline the objectives to carry out to answer those questions.

Chapter 3

The Adaptive Model for Digital Game Based Learning

3.1 Introduction

The primary aim of this thesis was to develop an Adaptive Model for DGBL (AMDGBL). This chapter presents the AMDGBL in detail and explains the choices made in how it was devised, with reference to sections of the literature review (Chapter 2). Figure 3.1 shows how the major sections of the literature reviewed informed the creation of the AMDGBL. The exception is VR, which is one of several mediums that could have been used, and the choice of which was informed by the analysis and design phase of the AMDGBL.

The chapter begins with a high-level overview of the model, such as the overall philosophy and the main phases of the model. The section also includes a high-level diagram of the model (Figure 3.2). Sections 3.3 to 3.8 describe the constituent phases of the model and the activities therein.

3.2 High-level Overview

Two of the key features of modern models of instructional systems design are *iteration* and *evaluation* (discussed in Section 2.5.5.8). Both feature strongly in the AMDGBL.

Agile software development, which underpins the processes of the AMDGBL,

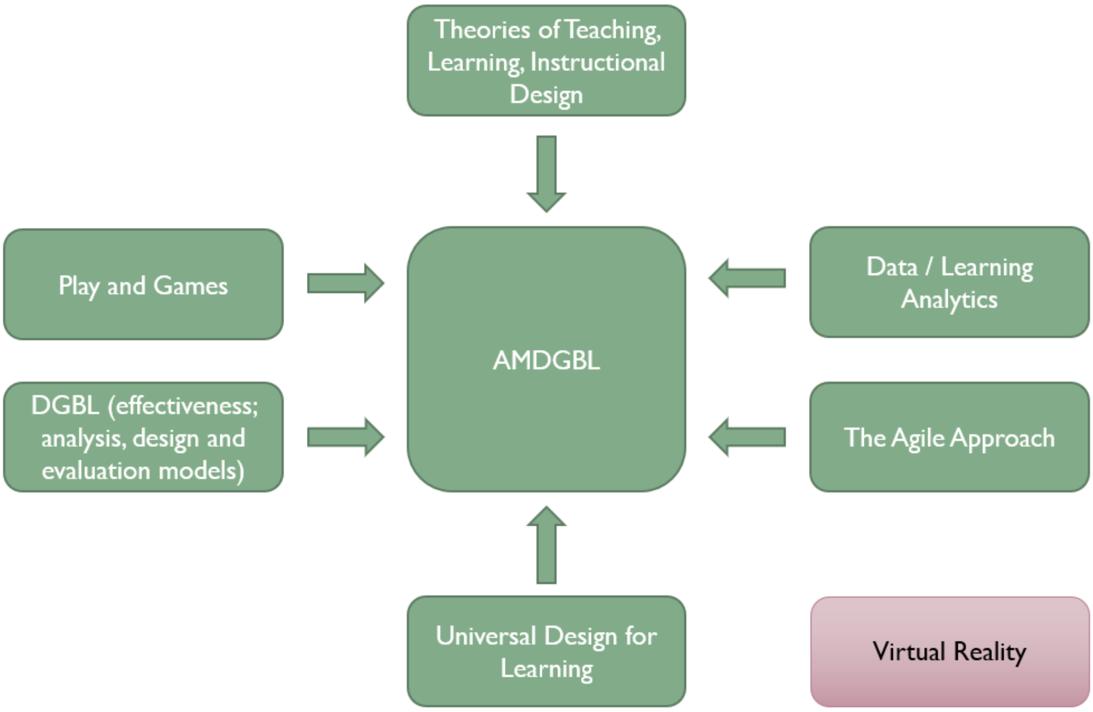


Figure 3.1: How the literature review informed the AMDGBL.

was discussed in Section 2.6. When adopting an agile project management framework, such as Scrum, iteration becomes rhythmical and part of the cadence of a project. There are many guides on effective implementation of Scrum, including one by a joint-publisher of the original Scrum framework, Jeff Sutherland, *Scrum: The Art of Doing Twice the Work in Half the Time* (2015). According to Schwaber (1997), "a successful development methodology must take [*customer requirements, time pressure, competition, quality, vision and resources*] and their evolutionary nature into account." In other words, requirements and context will change over time, particularly on a lengthy project, and a methodology must be responsive or agile.

Figure 3.2 shows a high-level view of the model (each phase will be expanded on in detail in later sections). The following steps outline the diagrammed process of developing a DGBL solution as a team (ideally, as Gagné et al. 1992, advise in relation to the design of all instructional materials):

1. An initial analysis and design phase sets out what is needed in terms of instruction and learning, including context, learning outcomes, learner profile, game mechanics and game structure. This phase produces a backlog of stories (individual requirements described in plain English at a high-level) to complete over the course of the project (the solution

backlog).

2. The outputs from the analysis and design are formatively evaluated from several perspectives, including universal design, motivation, flow, balance, narrative (if any) and serious game mechanics. The formative evaluation may lead to improvements in the design.

3. For each sprint (typically 14 to 30 days), a number of stories are selected from the backlog and these are worked on over the course of the sprint duration: in the tradition of Scrum, these stories are locked down for the duration of the sprint.

4. The DGBL developers then *pull* stories to work on—this is distinct from having them *pushed* by a project manager (for example, dictated by a GANTT chart). Developers iterate on a daily basis through further analysing stories, implementing them and unit testing them. Best practice would be to commit changes at least daily to a version-controlled central repository, such as git[1]. Where there are multiple developers, their changes should be continuously integrated to avoid later integration issues.

5. At the end of the sprint, it is mandated to have a functional prototype—in other words, something that can be run (played) and does not frequently crash.

6. Once it is verified that the updates of all developers are integrating (the DGBL solution builds without error), the new prototype is tested as part of a study featuring key stakeholders, which is not limited to learners and educators.

7. Ideally, multiple methods are used to formatively evaluate the prototype, such as observations, think aloud, surveys and analytics.

8. A sprint retrospective, which is embedded in the formative evaluation phase, identifies whether any additional stories should be added to the solution backlog (or if any should be modified or removed).

9. If another sprint is required, developers return to step 3 and iterate until there are no more sprints, in which case they continue to step 10.

10. The solution is now ready for delivery and is deployed to the environment it will run in for the learners (central web server, laboratory

[1]https://git-scm.com/

PCs, and so on). How the solution is integrated into the curriculum and lesson plans should have been determined in step 1 (context).

11. Assuming no major bugs are encountered (in which case developers produce a 'hotfix'), learners engage with the solution.
12. At intervals, such as at the end of a semester, a summative evaluation is performed to see if the stakeholders involved in the formative evaluations were typical of the wider population of learners and any other unforeseen issues occur.
13. Depending on the outcome of the summative evaluation, developers may develop hotfixes where necessary, or in the case of more significant improvements, return to step 1 and repeat.

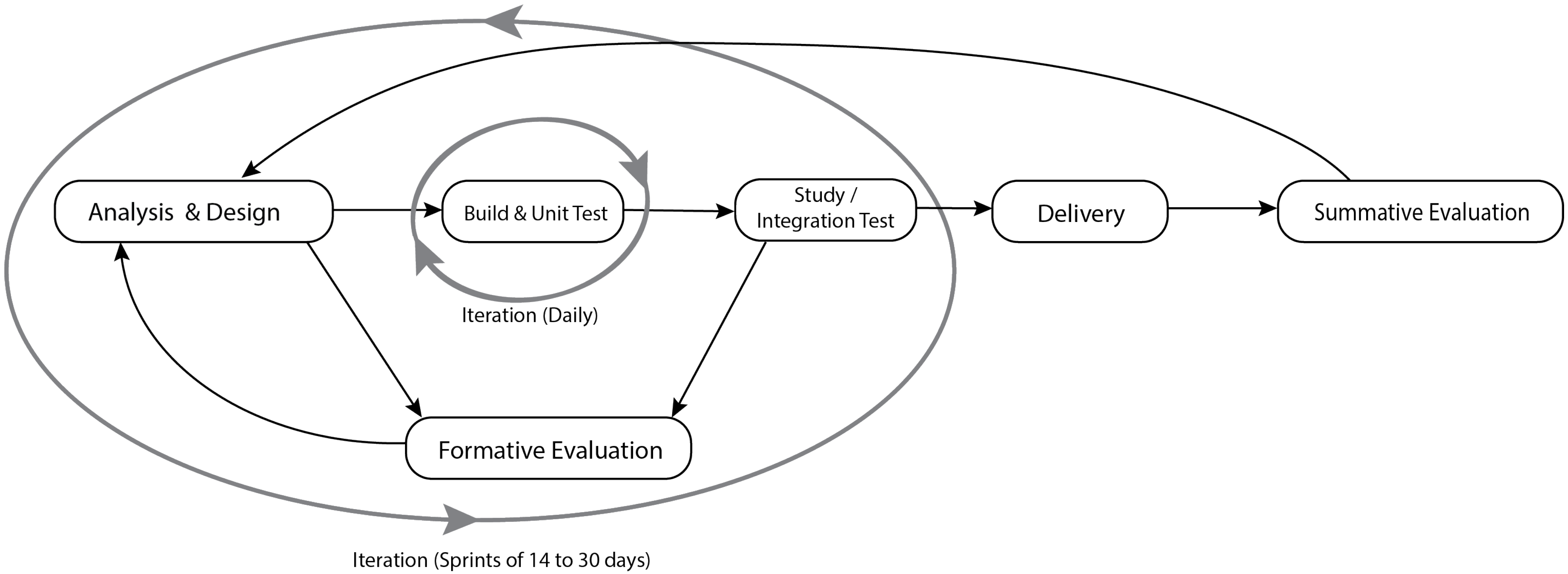


Figure 3.2: High-level diagram of Adaptive Model for Digital Game-based Learning.

The phases of the model are discussed in more detail in the following sections.

3.3 Analysis and Design

The analysis and design phase of the AMDGBL consists of at least the following steps (also illustrated in Figure 3.3):

1. A needs analysis;
2. Identification of learning outcomes;
3. Identification of type of learning required;
4. Identification of serious game mechanics (SGMs) to implement learning;
5. Mapping of SGMs to game dynamics;
6. Mapping of game mechanics to game dynamics;
7. Mapping of learning outcomes to learner interaction events;
8. Embedding learner interaction events in a game structure.

Most systematic models of instructional design begin with a needs analysis, as discussed in Section 2.5.5.8. Three of the dimensions of the 4DF model for DGBL (de Freitas and Oliver 2006) (discussed in Section 2.3.4.1) are context, learner specification, and pedagogic considerations and the framework includes a checklist with a series of questions that could be used to complete steps 1 to 3 above.

With the types of learning identified (for example experiential learning cycle, scaffolding, discovery learning, and so on), it is then possible to begin mapping the types of learning to SGMs. The LM-GM model discussed in Section 2.3.4.3 could be used for this purpose. SGMs are still high-level descriptions of the type of gameplay that should take place to deliver the required learning. Therefore, it is necessary to map the SGMs to game dynamics. For example, Section 2.3.4.3 provided the example of:

> the learning mechanics of *analyse*, *ownership*, *accountability* and *responsibility* implemented through the game mechanics of *design/editing* and *ownership*.

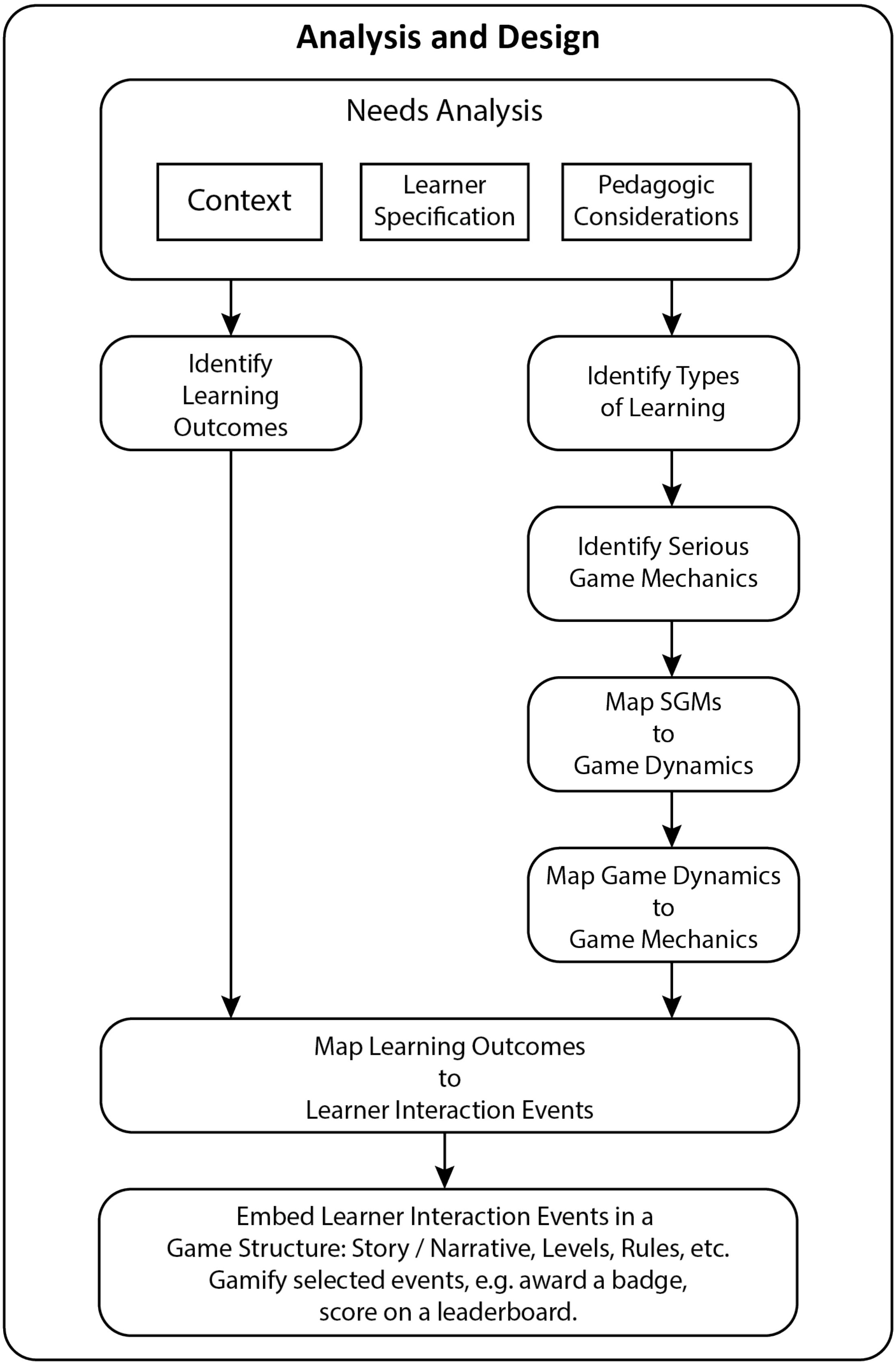


Figure 3.3: Steps in the Analysis and Design phase.

Only the game designer can map this example of SGMs to the game dynamic of writing and filing a story (the main protagonist in the example is an investigative reporter). Similarly, the game designer must then map the game dynamics to the game mechanics—the multiple use of the term *game mechanics* can be confusing; the LM-GM model writes about game mechanics in a high-level way, but game mechanics in the sense of the MDA model (discussed in Section 2.3.3.1) are low-level implementations. An example of this mapping would be to list the game mechanics of displaying a list of clues discovered on a 2D user interface with drag-and-drop capabilities, along with the ability to enter text in a text box and add it to a diagrammatic visualization of a story. Additional mechanics would include the storage and retrieval of clues and dialogue in a data structure.

Before discussing how the learning outcomes should be devised, it is worth highlighting that this step is optional. As noted previously (in the subsections under Section 2.5.5), some educators dislike the linear or hierarchical nature of taxonomies, and others are critical of their behaviourist approaches. If a purely emergent form of learning is desired, such as through open inquiry (described in Colburn 2000)), then the tight specification of intended learning outcomes would be undesirable.

Intended learning outcomes (if there are any) will be identified and typically mapped to a taxonomy, such as the revised Bloom's or Biggs's SOLO (both discussed in Section 2.5.5). High-level learning outcomes should be broken down into concrete learning outcomes. A high-level learning outcome might require several concrete outcomes to be observable. For example, a high level outcome might be to demonstrate an understanding of graph completion, but this might require the concrete outcomes of *understanding the concept of a vertex*, *understanding the concept of an edge*, and *understanding how to connect vertices using an edge*. Each of the concrete learning outcomes can be part of a learning path towards completion of a higher-level learning outcome and can be used to measure progress towards a higher-level learning outcome. It is possible to represent learning outcomes in a hierarchical tree structure where each of the leaves is something concrete (or can be observed to have taken place). There could, theoretically, be an infinite number of levels in the tree from top-level learning outcome to concrete learning outcomes. Figure 3.4 shows an example used later in Section 4.4.2 when describing the analysis and design of the graph game. The letters in brackets correspond to levels in the SOLO taxonomy: U = uni-structural, M = multi-structural, R = relational, E =

extended abstract. If a taxonomy is not used, then learning outcomes can be in a flat structure.

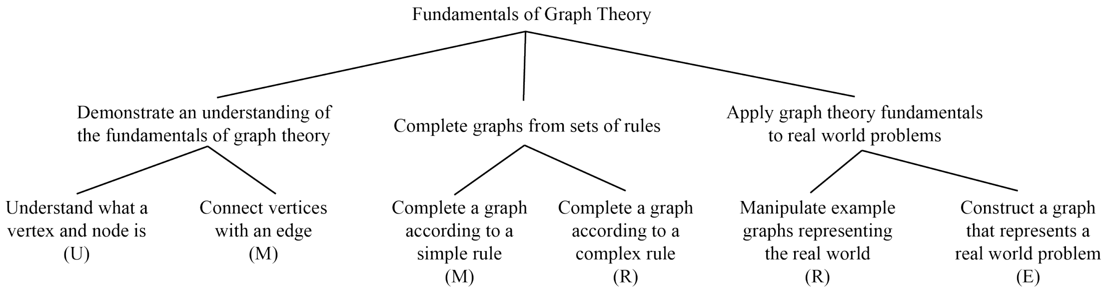


Figure 3.4: A hierarchical approach to learning outcomes.

With a structure of learning outcomes identified, it is then possible to map the concrete learning outcomes to learner interaction events. These events will be triggered by game mechanics in a game context. Therefore, the game's structure must be designed before the events can be embedded within it. For example, if certain fundamental concepts are taught as part of a tutorial level in a game, the mechanics that combine to teach the concept (for example, the display of instructions retrieved from a database and the correct actions of a learner when interacting with objects based on those instructions) will need to trigger a learner interaction event (such as "concept A has been learned").

Other aspects of constructing a game structure are discussed in Section 2.3.3 in terms of engagement and in Section 2.2 in terms of the typical components in a game. Games often feature levels which can contain sets of concrete learning outcomes and progressively increase along a taxonomy, for example from uni-structural to extended abstract using the SOLO taxonomy. The types of learning, identified as part of the needs analysis, may include pedagogical considerations, such as Kolb's experiential learning cycle (discussed in Section 2.5.5.6) and this would dictate facilitating active experimentation, concrete experience, reflection and abstraction—each level could consist entirely of this cycle; or a cognitive approach such as Bruner's spiral curriculum (discussed in Section 2.5.5.5) might dictate revisiting concepts in later levels in a more complex way.

Additional advice on how to make entertaining games can be found in game design texts such as Jesse Schell's *The Art of Game Design* (2015) and Scott Rogers's *Level Up! The Guide to Great Video Game Design* (2014). The former is one of the most comprehensive books on game design (with 112 lenses through which to examine the design of a game), which is equally scholarly and practical, whereas the latter provides a more step-by-step guide to designing games, including templates for game design documents.

3.4 Build

Each sprint will have a backlog of stories to complete. Developers pull stories from the sprint backlog (Scrum is implemented by self-organizing teams rather than a top-down approach where a project manager pushes tasks to developers) and make whatever changes are necessary to implement the story. This is then unit tested in isolation, but each should also be integrated continuously when unit tests verify the story has been implemented correctly. The seminal article on continuous integration (CI) (according to Duvall et al. 2007) was one by Fowler and Foemmel (2000), published as a post on Martin Fowler's website and later updated in Fowler (2006). Fowler defines continuous integration as:

> a software development practice where members of a team integrate their work frequently, usually each person integrates at least daily—leading to multiple integrations per day. Each integration is verified by an automated build (including test) to detect integration errors as quickly as possible.

The practices of the CI process, according to Fowler, are:

1. Maintain a single source repository;
2. Automate the build;
3. Make your build self-testing;
4. Everyone commits to the mainline every day;
5. Every commit should build the mainline on an integration machine;
6. Fix broken builds immediately;
7. Keep the build fast;
8. Test in a clone of the production environment;
9. Make it easy for anyone to get the latest executable;
10. Everyone can see what's happening;

11. Automate deployment.

Automation is key to CI. The team (if there is one) works from a central source code repository or “mainline” (if the platform can be developed using source code) and ensure they keep their local copy of the system up-to-date (by pulling down the latest updates from the mainline regularly).

The process of continuous integration, deployment and delivery is explained in some detail by Humble and Farley (2010) who refer to the iterative processes involved in software development and how the greater cost of software is incurred after the first successful release (with support, maintenance, bug fixes, new features, and so on). This would be particularly true of a DGBL solution where a long lifespan (five years or more) is envisaged. And it could be even more true of a DGBL solution in a quickly-evolving subject, such as STEM, law, medicine, and so on.

Of additional note is the concept of DevOps (a combination of development and operations), explained in *The DevOps Handbook: How to Create World-Class Agility, Reliability, and Security in Technology Organizations* (Kim, Debois, Willis, Humble and Allspaw 2016), which is built on agile processes, such as Scrum, CI and continuous delivery. The book explains how DevOps is a cultural shift where any persons involved in a project, such as developers, technicians, and those in quality assurance, colocate (or at least facilitate frequent communication) in cross-functional teams. In a DGBL context, this could involve lecturers or teachers, learner representatives, technology-enhanced learning (TEL) specialists, pedagogical experts, technicians, and so on, working together and cross-pollinating ideas. This is a significant shift from the situation that prevails in most educational institutions where TEL specialists tend to be housed in their own department (or “silo”) away from other staff involved in the delivery of TEL solutions.

3.5 Study

The study should involve selected learners, educators or any other interested stakeholders “playtesting” a functional prototype (or ultimately the final solution). Schell (2015, p.446), in his lens of playtesting, poses five questions:

1. **Why** are we doing a playtest?

2. **Who** should be there?
3. **Where** should we hold it?
4. **What** will we look for?
5. **How** will we get the information we need?

Answering those questions can help arrive at a protocol and methodology for the study, which will form part of the formative evaluation. The following answers could be applied in a DGBL context:

1. **Why** are we doing a playtest? To discover if the DGBL solution has met the goals of the sprint in terms of effectiveness, motivation, efficiency, balance, universality and several other criteria.
2. **Who** should be there? Key stakeholders such as learners, educators and potentially anyone else with a vested interest in the project succeeding.
3. **Where** should we hold it? Depends on medium—for example, a web-based or mobile solution could be playtested remotely, but if there are to be observations or a think aloud protocol in place, in person in a suitable laboratory environment might be preferable.
4. **What** will we look for? Partly answered by the *why* question: usability issues, pedagogical issues, balance issues, and so on.
5. **How** will we get the information we need? By employing whatever methods will give us the answers we need, whether this is observations, think aloud, surveys or analytics; or a combination of all of the above.

Rather than going into significant detail here, Chapter 5 shows how a comprehensive study can be carried out. Key to the approach is the iterative nature of the study. Each study takes place at the end of a sprint with a limited number of study participants. Jakob Nielsen (2012) suggests five participants will discover about 80% of all usability issues. If there are multiple sprints, it stands to reason that usability issues not discovered in a previous sprint have a high probability of being discovered after a subsequent sprint (unless they are rarely-occurring issues). Any remaining issues can be identified as part of a summative evaluation post-delivery.

This approach is similar to one outlined by an employee of Valve software (developer of games like *Half-Life 2* and *Left 4 Dead*), experimental psychologist Mike Ambinder, during a presentation at the *2009 Game*

Developers Conference (Ambinder 2009). Valve's philosophy is to "make informed decisions" by getting data early and often and to "iterate constantly", to "create a feedback loop between design and playtest". Several methods are employed during their playtests, including direct observation (in a simulated home environment as opposed to a laboratory environment) and verbal responses (think aloud protocol)—the two are used in conjunction with each other. Valve also employ technical playtest methods, including data analysis and surveys. While similar to the methods outlined in Chapter 5, the focus is marginally different: while a study of an entertainment game can focus on how much fun a player is having, a study of a DGBL solution needs to focus both on fun and pedagogical considerations (Serrano-Laguna et al. 2017), thus arguably making it a more complex study.

3.6 Formative Evaluation

Formative evaluation of DGBL solutions is an evaluation of the process of intervention more so than whether the intervention has attained overall goals, which is more suited to a summative evaluation (All et al. 2016). Formative evaluation was considered separate to the *study* phase because it can occur prior to the first development sprint commencing. When the initial solution backlog is devised in the analysis and design phase, along with any paper-based or digital prototypes (sketches or maps of level designs, for example), the design can be evaluated in a formative sense using some of the tools (models, lenses and frameworks) outlined in previous sections. The following list suggests some of the ways in which a design can be evaluated formatively, along with suggested models and frameworks:

1. **Universality** with the UDL framework (discussed in Section 2.7.2). Each of the 31 checkpoints can be examined to see if the proposed design has addressed issues of accessibility, usability, self-regulation, relevance, and so on.

2. **Serious Game Mechanics** with the LM-GM model (discussed in Section 2.3.4.3). The LM-GM model can be used to come up with an initial design of how learning mechanics map to game mechanics, but it is also an evaluation tool.

3. **Balance** with Schell's lens of challenge (discussed in Section 2.3.3.2).

The six questions can be answered to evaluate how successful the design appears to be in terms of the balance of both instructional materials and any exercises or assessments included. In other words, is the game too easy or too hard and does the level of challenge progress in a way that players can achieve (or be accommodated to achieve depending on learner ability)?

4. **Flow** with the mapping of flow elements to game elements (see Table 2.3). This is a checklist to evaluate to what extent the design will facilitate focus and flow.

5. **Motivation** with one or more of Csikszentmihalyi's guidelines for creating intrinsically motivating activities (Table 2.5), Schell's lens of motivation (Table 2.6) or Schell's lens of novelty (Table 2.7). There are some overlaps between motivation and range and level of challenge according to Csikszentmihalyi.

6. **Narrative** with Narrative Serious Game Mechanics (discussed in Section 2.3.3.4).

Once playtesting has taken place in a post-sprint study, the data gathered from the various methods employed can be analysed. Observational and think aloud notes can be examined for usability issues, levels of engagement (or fun), pedagogical issues, and so on. Surveys can provide findings on either perceived (for example, participants agreeing strongly that they learned effectively or were highly motivated to learn) or actual effectiveness (with empirical evidence). Actual effectiveness could be evaluated with pre- and post-questionnaires, for example testing knowledge before a game is played and testing again afterwards. Ideally, at least a quasi-experimental study (explained in Cohen et al. 2017, p.405-7) such as this would be carried out to compare a DGBL solution with an alternative (perhaps traditional) approach with one or two groups—however, this would significantly increase the amount of time, effort and number of participants and may only be suited to a summative evaluation (as suggested by All et al. 2016), as discussed in a later section; it is unlikely to be suitable for the frequent iteration of an agile approach, such as the AMDGBL.

Even with small amounts of gameplay data gathered, it could be possible to identify issues of balance or engagement through visualizations. In that respect, the designer might borrow aspects of the summative evaluation (discussed in Section 3.8), depending on certain factors, such as budget and the number of participants in the formative evaluation studies. Average total play times or durations to complete specific exercises can be visualized, though it may take two or more iterations for statistically-significant standard deviations or outliers to emerge. Significant numbers of outliers (or even a single outlier in some cases) can point to issues of usability or pedagogy.

With the additional findings from the data gathered in hand, it is possible to revisit suggestions 1 to 6 above and answer questions with a higher degree of confidence. The findings and the answers will feed into a sprint planning activity to identify whether modifications to the solution backlog are required and to prioritise stories for the next sprint backlog.

3.7 Delivery

Ultimately, most projects are deadline driven. An example deadline would the start of the school or college year. The DGBL solution must be deployed to a production environment, whether this is a download location for a mobile app, laboratory PCs, a website, and so on. Delivery should be relatively straightforward if the principles and practices outlined in Section 3.4 have been followed, such as ensuring that test environments mirror the production environment. In addition, if a proper needs analysis was carried out, then the context and the learner profile will already have been known and planned for. How the new DGBL solution will be embedded within the curriculum and in lesson plans should also have been carried out as part of the needs analysis.

3.8 Summative Evaluation

Whereas formative evaluation necessarily deals with smaller numbers of learners to make the iterative approach viable, a summative evaluation is an opportunity to examine all data and to have the performance of the DGBL solution evaluated by more people. Summary and comparative analysis and visualizations can be carried out. A summative evaluation provides the fullest possible picture about the success or otherwise of a DGBL project, but it usually does so after the initial delivery of a solution to learners (as discussed in Peterson (2003), for example). It is an opportunity to establish, using experimental designs, if the overall goals of the intervention have been attained (All et al. 2016).

Two alternative approaches could be envisaged:

1. At the end of the final sprint, and before delivery, combine all of the data from the previous formative assessments and re-analyse. This could give a fuller picture than just one last small formative evaluation, but would run the risk of including stale data—some issues will have been resolved and could taint the findings.
2. Perform a larger final formative assessment. This could be at the level of a true or quasi-experimental study with pre- and post-tests (as explained by Cohen et al. 2017, p.405-7), but it might build confidence that the solution is ready to be delivered, or identify if it needs further work.

The latter approach is similar to what is known in agile software development as a “hardening” or “release” sprint (Cohn 2007), where the final sprint before a release is used to work on tasks related to getting the software ready for release and to make up for any shortcomings in engineering practice in the previous sprints; this includes more rigorous testing to identify, in particular, integration issues. This would be more applicable to larger projects where there are many components to integrate.

3.9 Chapter Conclusion

This chapter set out, with reference to the extensive literature review carried out, the structure and the processes in the AMDGBL. The diagram highlighted the iterative and agile nature of the model and how formative evaluation is at its heart. The model begins with a comprehensive analysis and design phase that aims to establish the learning context before mapping out the learning in terms of outcomes and how the learning should be carried out (with reference to the theories of learning discussed earlier). The analysis and design phase also includes how the learning mechanics are mapped to game mechanics and how the game mechanics are to be implemented in the game to create game dynamics. Finally, the analysis and design phase embeds data gathering in a game structure comprised of the game dynamics with embedded learning. The build phase of the model discusses agile processes and suggests a DevOps approach where cross-functional teams cross-pollinate ideas and skills. The study phase outlined how, much like playtesting is carried out in the video games industry, multiple methods can be employed. The formative evaluation phase outlined how both the design and prototypes (with the aid of data analytics) can be evaluated from several perspectives, including universality, serious game mechanics, balance, flow, motivation, and narrative. The delivery phase briefly discussed how the game will be embedded in the curriculum and lesson plans. The summative evaluation phase discussed when it should be carried out and to what extent.

Chapter 4

The Graph Game and the Learning Analytics Platform

4.1 Introduction

Both the Graph Game and the Learning Analytics Platform (hereafter simply referred to as the game and the platform) were an integral component of the research instruments in both studies. The AMDGBL was followed when developing the game and the platform. Therefore, it is important in the following sections of this chapter to go into detail on the methods used to design, build and evaluate the game and platform.

The chapter begins with Section 4.2, which is an overview of the agile methodology used to develop the prototypes.

Section 4.3 details the design and development of the platform.

Section 4.4 details the design and development of the game.

Section 4.5 details an evaluation of both the game and the platform using the UDL framework.

4.2 Use of Agile Methodology

Though this was not a team-based project, a Scrum-like approach to agile software development was used. Trello[1] was used to manage the backlog of stories (individual requirements) in a left-to-right (backlog-to-completion) workflow on what is called a *board*. It resembles cards being pinned on a cork board, or Post-It notes on a whiteboard, and its drag-and-drop interface is flexible.

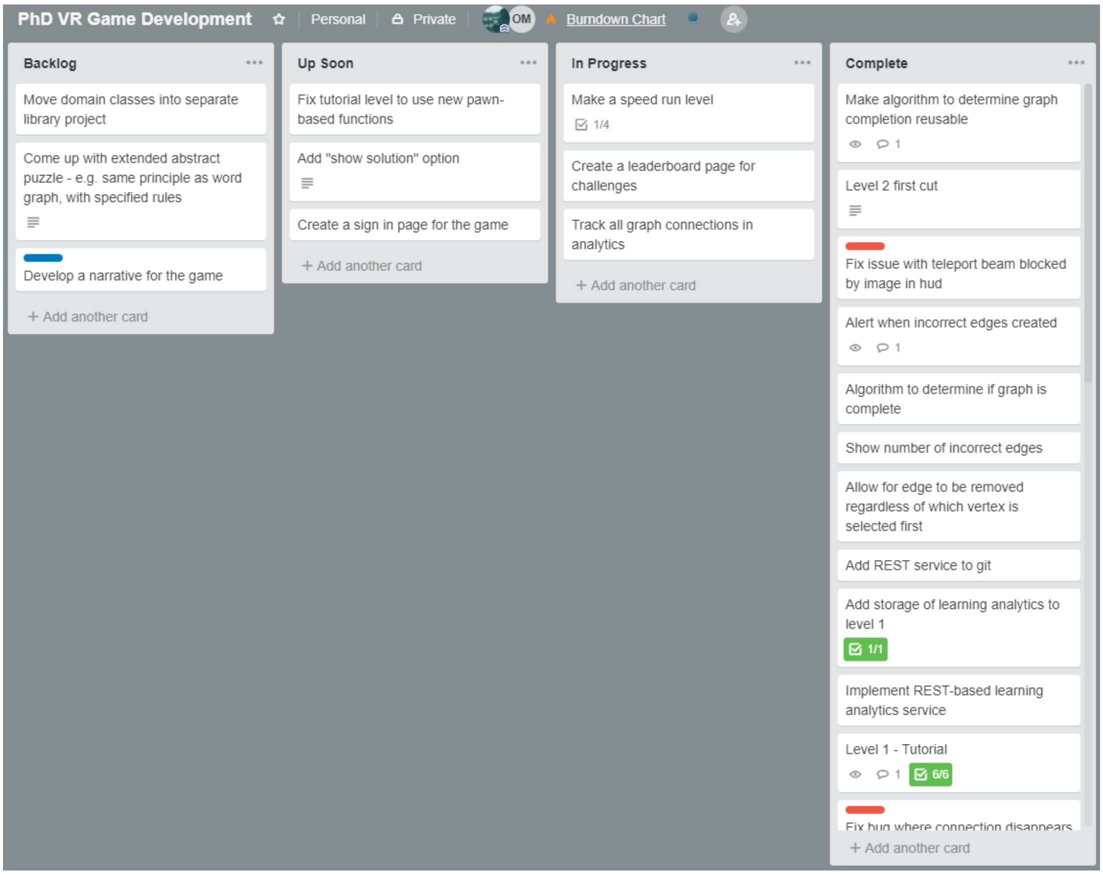


Figure 4.1: The initial Trello board used to develop the prototypes

Figure 4.1 shows a snapshot in time of development of the graph game and DGBL platform. The board in Figure 4.1 was used for development of the prototypes up to the first study. The learner study was split into smaller sprints, with changes to be made (stories), which were identified following each cohort of participants, added to the backlog for each sprint. This iterative approach is discussed in more detail in Section 5.3.1.

[1]http://trello.com

4.3 The DGBL Platform

The DGBL platform consists of two components: an application programming interface (API) and a web-based dashboard. The design and implementation of both are discussed in this section.

A key objective of the platform architecture (Figure 4.2) was to make it flexible enough to support multiple DGBL solutions and to support access to the data generated by the games via an API. In the DGBL platform developed, the use of data consisted of visualizations, but with its API, the data could be used by other applications, such as data exporters to virtual learning environments (VLEs) using industry standards such as xAPI[2]. The use of industry standards, such as xAPI, is suggested by Serrano-Laguna et al. (2017), though as the authors note, xAPI it is not without its drawbacks for gameplay data and so the approach of a custom API from game to platform with a separate standards-based service (which might replace 'App 2' in Figure 4.2, for example) to export summarised data to xAPI-compliant systems (e.g. VLEs), might be the best approach.

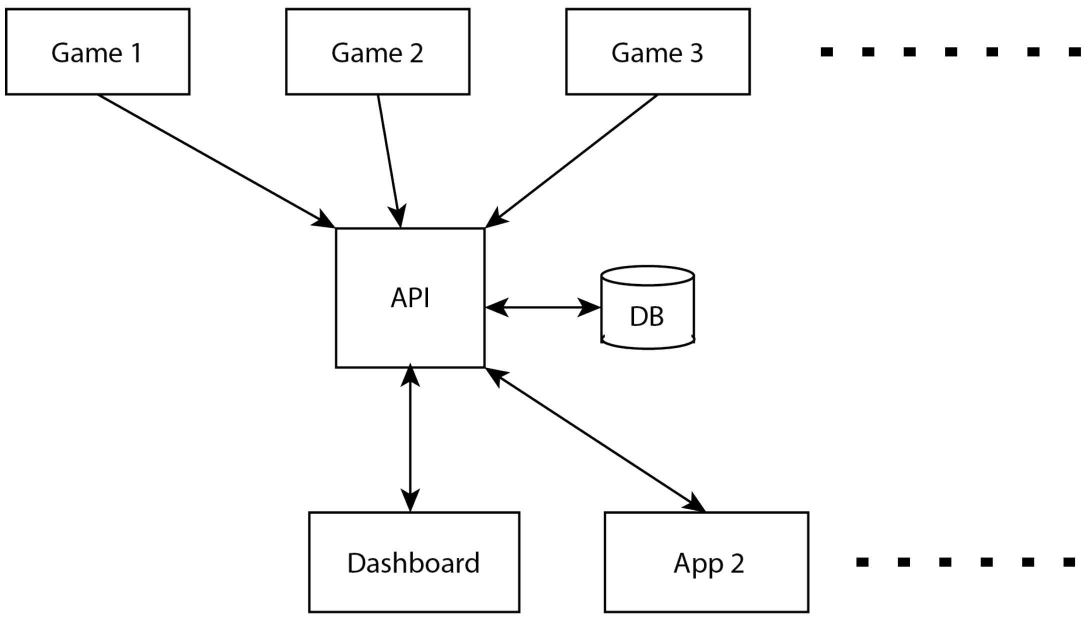


Figure 4.2: The DGBL Platform Architecture.

The platform is a bespoke one and, while novel, is not entirely unique in its approach. It is novel in the sense that DGBL LA platforms are rare (as suggested by Serrano-Laguna et al. 2017). When development began on this

[2]https://xapi.com/overview/

platform, a search of the literature was performed. No similar system was found and development progressed. However, the researcher initially missed one project of interest: The REAPER project, funded by the European Union's Horizon 2020 fund (specifically under FP7). The project was first (based on a search through the literature) presented in Baalsrud-Hauge et al. (2015), which, like the research for this thesis, noted the absence of a systematised platform for game-based learning analytics. The platform later became known as RAGE Analytics and is further outlined in Alonso-Fernandez et al. (2017). This scenario is common (two projects being initially unaware of each other proceeding in parallel); the original 2015 paper was not widely cited and the researcher was still new to the DGBL discipline. The question then is whether there is value in a separate DGBL LA platform. The answer, for the research in this thesis, is arguably 'yes'. Apart from choice being a good thing (for instance, the API of this thesis is a custom one focused on game-based learning, whereas RAGE Analytics uses xAPI, which is a general specification), there were several visualizations required that RAGE Analytics could not provide without modification (such as the violin plots to evaluate game mechanics for outliers in Figure 5.13 in Chapter 5).

This left two options: develop a bespoke solution, or extend the functionality of the RAGE Analytics platform (necessitating becoming deeply familiar with the implementation). The former was chosen due to the greater degree of control and freedom (and existing software development expertise), though the latter remains a possibility. The former option had already begun before the latter was considered, and so there was already an inertia to it that resisted a change in course. Ultimately, there would be two competing solutions and in an ideal world each would have their advantages and disadvantages that DGBL designers could assess before picking the right platform for their project.

4.3.1 The API

MuleSoft defines an Application Programming Interface (API) as

> a software intermediary that allows two applications to talk to each other. (Mulesoft 2016)

When referring to the API in the platform, it not only includes the intermediary software, but also a set of services for data storage and retrieval. It is these data storage and retrieval services that decouple data storage from each game. If each game had a local database, it would not be possible to analyse aggregated data to gather insights about the way learners learn, how engaged they are, or to allow for comparisons between learners. It also allows for the centralization of administrative services, such as backup and recovery.

When software communicates, a mechanism and data representation format must be chosen. The use of REST and JSON are becoming almost a de facto standard for the transfer of data between systems and this was chosen for the DGBL platform API.

An important design decision needed to be made up front. There are many types of interaction a learner might have with a game. Satisfying learning outcomes is just one. Others include the awarding of badges and the recording of challenge scores. Rather than try to anticipate all possible learner interaction types for an unknown number of future games, it was decided to have a single generic interaction type. This meant that the API would never be concerned about what types of learner interaction were taking place and would effectively become a *dumb* API. This shifted the responsibility of interpreting the data to the applications using the data, such as games and dashboards.

The communication mechanism chosen was REST (REpresentational State Transfer), a mechanism first proposed by Fielding (2000). Rather than being a standard set down by a particular standards organisation, such as the World Wide Web Consortium (W3C)[3], REST is an architectural style. It is a stateless architecture, meaning systems that communicate are unaware of each other's state from one communication between them to the next. This allows these systems to be entirely decoupled from each other with only the structure of the messages they send each other being shared (in other words, they speak a common language). REST also has the advantage that it uses standardised HTTP (HyperText Transport Protocol) operations, such as GET, PUT and POST, for retrieval, creation and updates respectively.

REST deals with resources (nouns) rather than commands (verbs). The most important resource in the DGBL platform from a learning analytics perspective is the *learner interaction*. REST is also about *representation* (which is the RE in

[3]https://www.w3.org/

the acronym). In other words, a representation of a resource (or resources) is sent between systems using a common language. The common language chosen to represent resources in the platform was JSON (JavaScript Object Notation). JSON uses a simple notation for the creation of *documents*—the resources sitting behind the *RESTful* endpoints are transmitted as JSON documents. When APIs are implemented using the conventions of the REST architectural style, they are often said to be RESTful (for example, see Garriga et al. 2016).

The full specification of the API is in appendix C. Listing 4.1 shows an example of an incoming JSON request (e.g. from game to API) that communicates the completion of a learning outcome. The request sends the game label (the `game` attribute value is `"graph"`) and the learner user token (the `learner` attribute value is `"123456"`). This allows the API to validate the game registration (a learner is registered to one or more games). The `type` and `key` attributes identify which specific learner interaction is being communicated, in this case the type `"learning_outcome"` indicates a learning outcome has been completed and `"graph_complex_rule"` is a key that matches to learning outcome 2(b): "Complete a word graph according to a complex rule" (see Table 4.1 for the list of learning outcomes mapped to the SOLO taxonomy).

Listing 4.1: Learner Interaction: Learning Outcome Completed

```
{
  "game": "graph",
  "learner": "123456",
  "type": "learning_outcome",
  "key": "graph_complex_rule",
  "value": "",
  "timestamp": "2018-01-01T09:15:00.345Z"
}
```

Listing 4.2 is an example of a challenge score request (type `"score"`). The key `"speed_run_1"` identifies it as the timed challenge at the end of level three. In this example, there is a score (time elapsed) in the `value` attribute. This is what Alonso-Fernandez et al. (2017) would call a *meaningful variable*.

Listing 4.2: Learner Interaction: Challenge Score

```
{
  "game": "graph",
  "learner": "123456",
  "type": "score",
  "key": "speed_run_1",
  "value": "274.225311",
  "timestamp": "2018-01-01T09:15:00.345Z"
}
```


The examples in listings 4.1 and 4.2 use the same API endpoint for saving learning interactions, which is specified in Section C.3. An example API endpoint for saving learner interactions is:

`http://127.0.0.1:8080/api/learnerInteraction`

In the example above, the server ip address is `127.0.0.1` and the port number is `8080`, though either can be configured differently.

The body of the request posted to the API endpoint would include a JSON document, such as the ones in listings 4.1 and 4.2.

4.3.1.1 Implementation of the API

Spring Boot for Java[4] was chosen as the software development framework with which to implement the API. The researcher has significant experience of using and teaching the framework and it was deemed very suitable for the development of a RESTful API (the Spring Web MVC project[5] explicitly supports REST).

The API was developed using a layered architecture. Figure 4.3 is a high-level diagram illustrating the abstract components in the layered architecture in the API—Appendix D.3 shows in more detail all of the concrete components in the API application.

Layered architectures allow for a "separation of concerns", which allows decoupled components to concentrate on doing one thing well rather than coupling together unrelated concerns (the principles of separation of concerns and single responsibility are discussed by Martin 2011). A *concern* in software engineering terms is a distinct type of functionality—examples include data

[4] https://spring.io/projects/spring-boot
[5] https://docs.spring.io/spring/docs/current/spring-framework-reference/web.html

access, logging and the display of information in a user interface. Designing components in this way makes them easier to maintain and reuse, and allows for systems to be restructured or reengineered more easily.

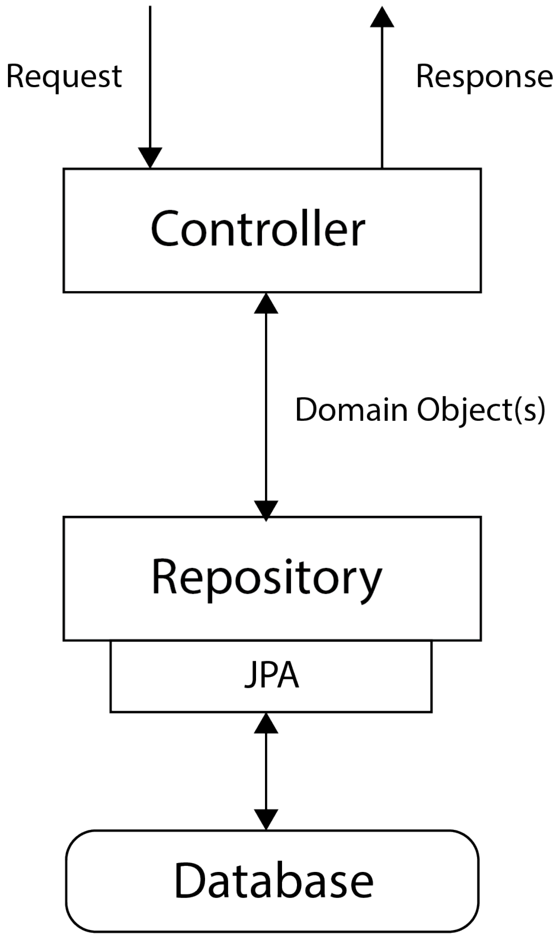


Figure 4.3: Architecture of the API

In the DGBL platform API, there were multiple controllers and repositories. A controller is a type of component concerned with handling client requests, processing them and returning any results. When processing requests, the controller will often delegate to other components, such as repository components, which access the database. This is an example of separation of concerns: the *client request handling* concern has been separated from the *data access* concern. One advantage of this approach is that the repository component can be reused by other controller components. For example, all of the controller components in the API use the GameRegistrationRepository component to check if the learner and game parameters received in a client request match with an existing game registration (note that all source code is available in a public GitHub repository—see Appendix D.4 for the hyperlink).

An example of these controllers is the `LearnerInteractionController` component. This receives requests directed to several endpoints, including the one specified in Appendix C.4, which retrieves a list of learner interactions for a given type for a given game registration. To carry out the request, the controller coordinates the delegation of parts of its algorithm to several repositories:

1. GameRegistrationRepository: to validate and retrieve the learner-game registration.
2. LearnerInteractionTypeRepository: to validate and retrieve the learner interaction type.
3. LearnerInteractionRepository: to retrieve a list of learner interactions.

4.3.1.2 Data Storage and Retrieval

A relational database was designed (see the entity relationship diagram (ERD) in Appendix D.1) and implemented using MySQL Community Server[6].

Probably the most important entity in the ERD is the `Game Registration` table, which links a learner to a game. The platform allows a single learner to be registered for multiple games. The `Game Registration` table is associated with the generic `Learner Interaction` table—this allows learner interactions to be linked to a specific game played by a specific learner.

The `Game` table, on the other hand, is associated with the `Learning Outcome`, `Badge` and `Taxonomy` tables. Some learner interactions will be related to learning outcomes and badges, but only indirectly using the `Learner Interaction Type` table. For example, one learner interaction type is "achievement". When a learner interaction has that type, there is an indirect connection between the learner interaction and a row in the `Badge` table. That badge will have a description that could be displayed in-game or in the dashboard. However, the responsibility for such indirect relationships rests with the developer who must know about the relationship (because it does not appear in the ERD) and code queries accordingly.

Spring Data JPA[7] was used to implement the repository components. A feature provided by Spring Data JPA is coding database queries by convention. For

[6] https://dev.mysql.com/downloads/mysql/
[7] https://projects.spring.io/spring-data-jpa/

example, the `findByGameRegistrationAndTypeOrderByTimestampAsc` method (or function or subroutine) in `LearnerInteractionRepository` is named according to this convention. Breaking the name down, it can be converted to a pseudo-SQL query, as per listing 4.3.

Listing 4.3: Pseudo-SQL for Retrieving Learner Interactions

```
SELECT a list of LearnerInteractions
FROM LearnerInteractions table
WHERE the GameRegistration matches the provided GameRegistration
    parameter, gr
  AND the LearnerInteractionType matches the provided
      LearnerInteractionType parameter, lit
ORDER BY the timestamp in ascending order
```

Spring Data JPA uses the object-relational mapping (ORM) library, Hibernate[8], by default and this generates the SQL query that MySQL can execute.

4.3.1.3 Use of the API in the Graph Game

Unreal Engine 4's gameplay framework[9] includes a base `Pawn` class. In the graph game, this has been extended with additional functionality as the `MotionControllerPawn` class. The pawn object is available to any of the other objects in the game, allowing any of its functions to be called from any Blueprint actor (an object in a level with behaviour) within the game or from the level's main Blueprint (where the game's top-level rules can be implemented). This made the `MotionControllerPawn` class an ideal location for scripts that connect to the API to send a request or receive a response.

For example, in the tutorial level it was possible to execute this API script by calling the `Store Analytics` function in `MotionControllerPawn`. An example is when the player first grabs a vertex, something that indicates progress has been made in learning the mechanics of the game. This calls the `Store Analytics` function with the learner interaction key value "tutorial_grab" (see Figure 4.4). The function call is handled in the pawn object, executing a script that connects to the API and sends a JSON request containing the learner interaction data (see Figure 4.5).

[8] http://hibernate.org/

[9] https://docs.unrealengine.com/en-us/Gameplay/Framework, accessed 01-Nov-2018

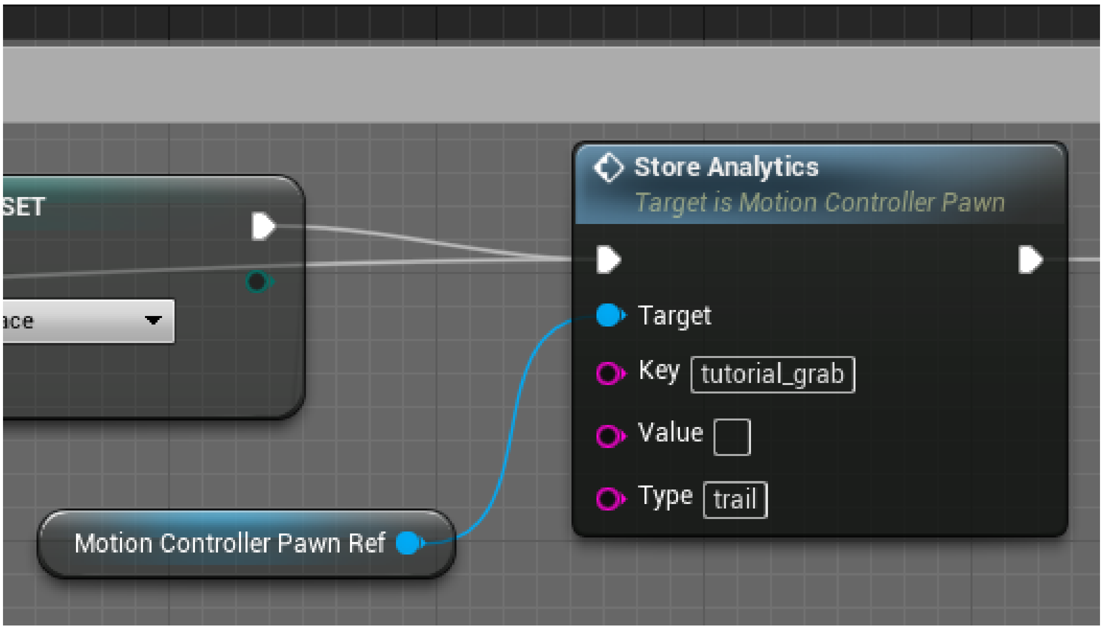


Figure 4.4: Calling the `Store Analytics` function from the tutorial level.

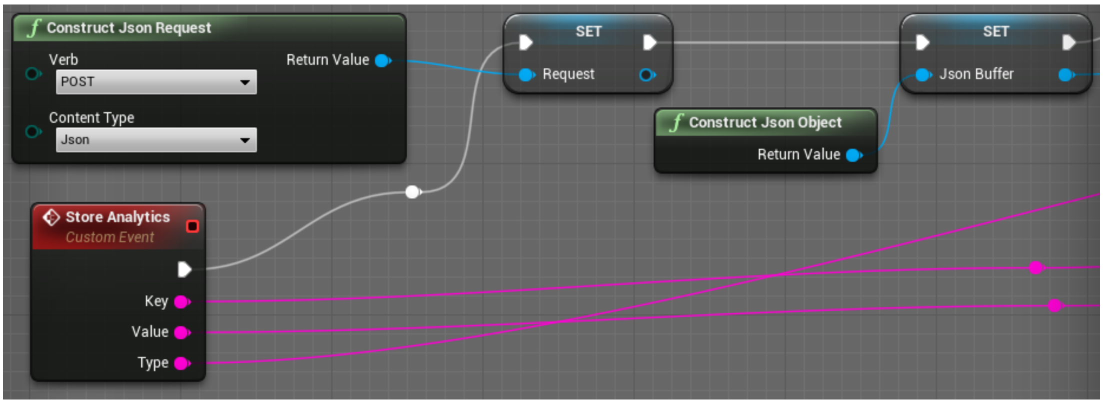


Figure 4.5: Part of the player controller `Store Analytics` function.

Figure 4.4 shows the construction of a learner interaction request of type *trail*, which is for adhoc events (or keeping an audit *trail*). More specific types exist. Figure 4.6 shows a score value (time taken) being stored in addition to a key and value. Figure 4.7 shows the *graph_complete learning_outcome* being stored.

4.3.2 The Dashboard

Section 2.8.1.1 discussed how LADs are a recent and effective way of informing and empowering learners. This section presents the design and

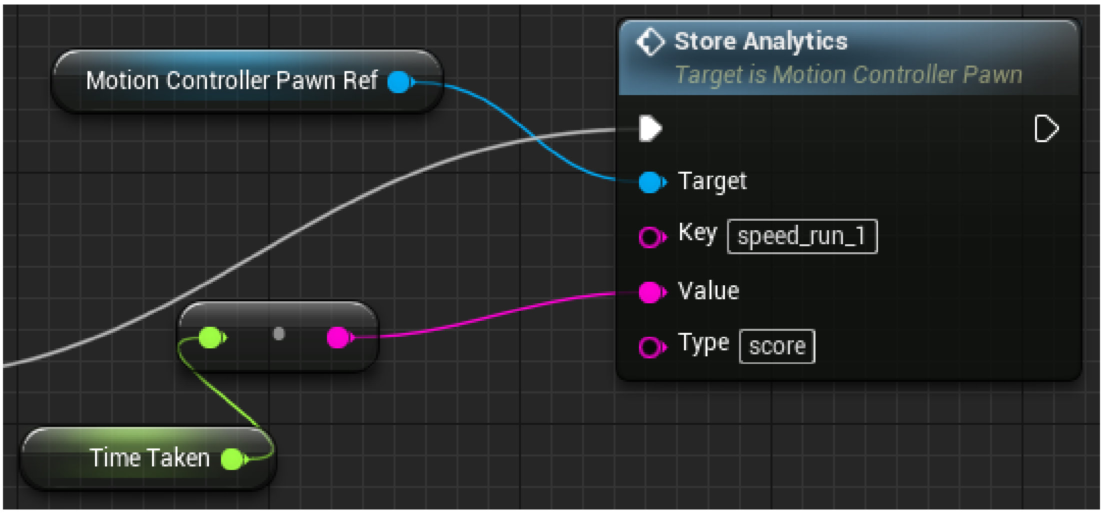


Figure 4.6: Storing a player score.

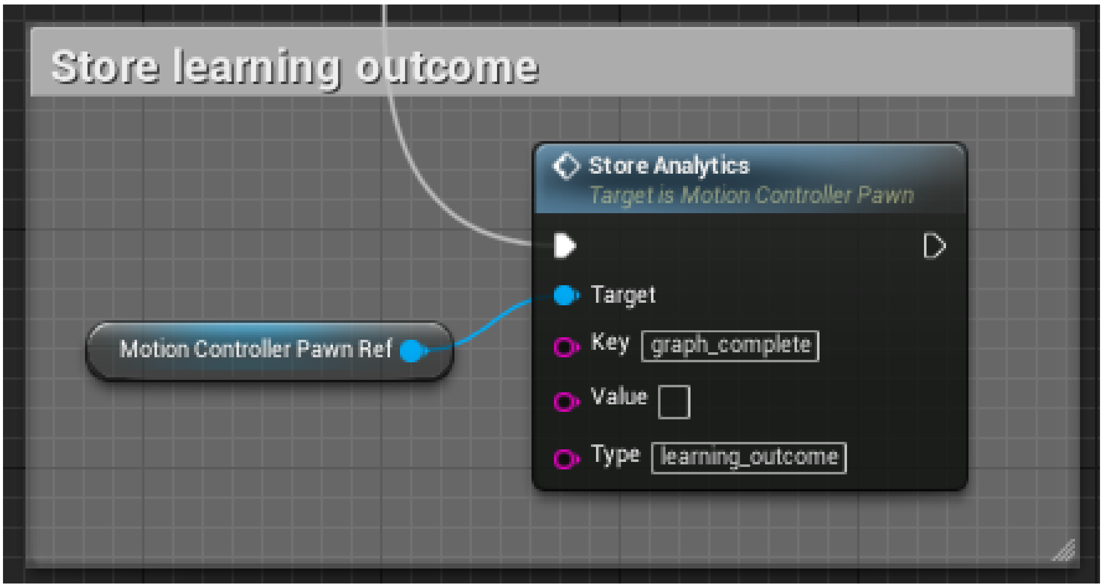


Figure 4.7: Storing a learning outcome.

implementation of the AMDGBL dashboard.

A review of the literature in 2.8.1.1 found that there were a number of principles that were associated with effective dashboards. These principles included avoiding information overload and providing drill-down capabilities. Figure 4.8 is the home page of the dashboard web-based application. It adopts the principles in a number of ways:

1. Information overload is avoided by only providing the most up-to-date, and therefore relevant, information in *pods*.

2. Drill-down capabilities (via the *See all...* hyperlinks) allow the user gain access to more complete information.

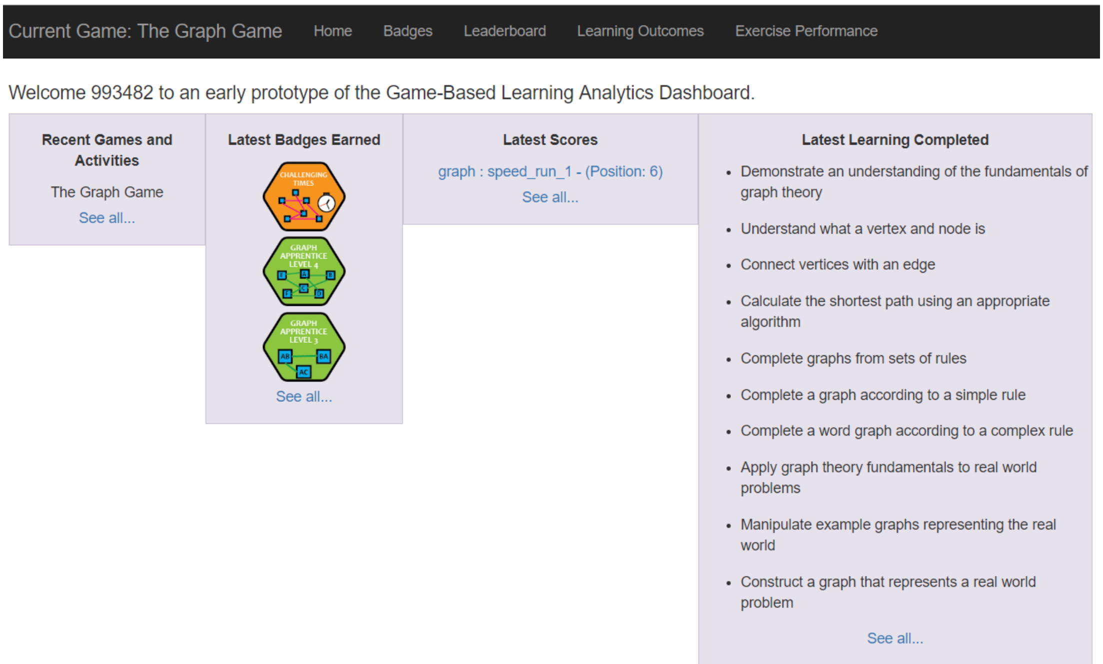


Figure 4.8: Main dashboard page.

Each of the drill-down hyperlinks, when clicked, brings the user to additional data and further visualizations. For example, on the main dashboard page, the *Latest Learning Completed* pod contains a log of the latest learning outcomes completed; clicking on *See all...* loads a more detailed visualization (see Figure 4.9) of learning with learning outcomes mapped to the SOLO taxonomy (as discussed in Section 4.4.2).

4.3.2.1 Implementation of the Dashboard

One of the primary aims when designing the AMDGBL platform was to have a decoupled architecture. This meant that rather than coupling the API and the dashboard into a single monolithic application—this means a single large source code repository offering many services, such as web-pages or web services (Villamizar et al. 2015)—the dashboard would be a separate application that treated the API as a separate data source. A monolithic approach would have quickened and simplified development of the platform, but a conscious decision was taken to aim for flexibility and scalability,

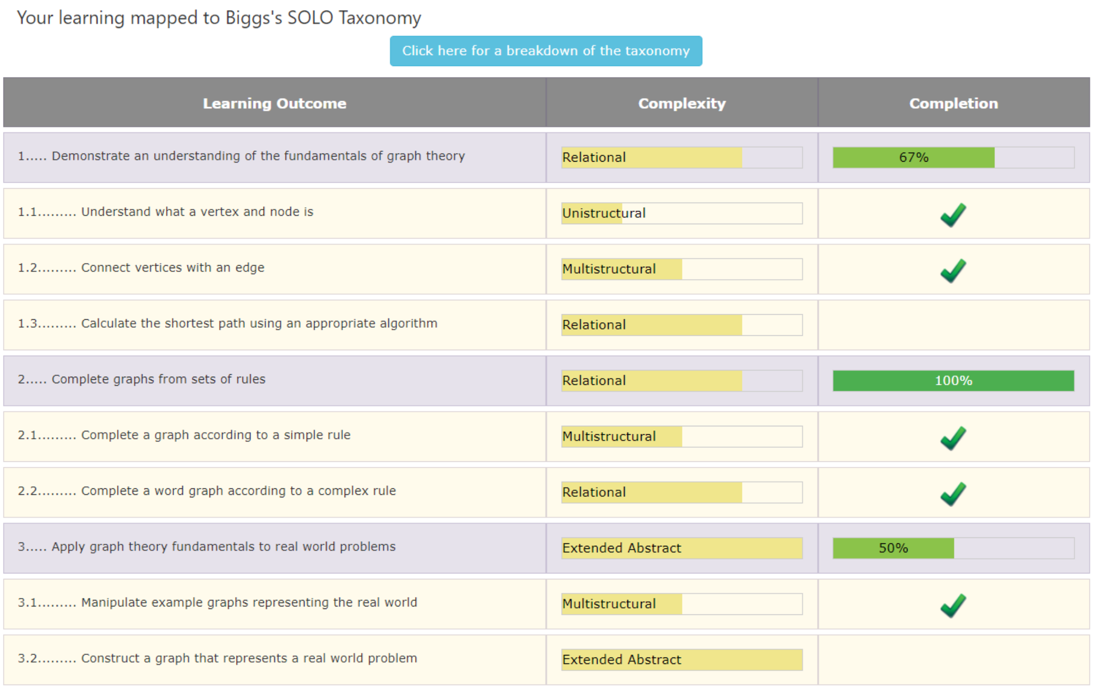


Figure 4.9: Visualization of learning mapped to the SOLO taxonomy.

allowing for growth in terms of the number of ways the captured data can be used.

Because the API was implemented as a set of RESTful web services, with JSON used as the technology for the encoding of requests and responses, the dashboard became a RESTful client of the API. When data was required to create a visualization on a web page, a JSON request would be sent to the API and a JSON response returned. It was then up to the dashboard client to parse (or deserialize) the JSON into the data to be presented.

A combination of technologies was used to implement the web page templates. This included Thymeleaf[10], which allows script to be embedded in a web-page, and Bootstrap[11], which is a front-end component library that includes, among other features, cascading style sheet (CSS) themes that allow web pages to be constructed in a consistent and responsive (in the sense that it supports mobile as well as desktop devices) way.

The dashboard application was developed using a model-view-controller (MVC) architecture (Leff and Rayfield 2001), which allowed for a separation of model (data and the code that interacts with the data) and view

[10]https://www.thymeleaf.org/
[11]http://getbootstrap.com/

(implemented using Thymeleaf and Bootstrap). In the middle, handling browser requests, is the controller. The dashboard application has a single `DashController` class which maps browser requests to the methods (or functions) that handle the requests.

An example (shown in Listing 4.4) is the `/badges/game/userToken` mapping to a method `getBadgesByGameAndUser` that retrieves the data from the API (via a request to `/api/learner/game/userToken/badges` in line 6), adds the data to the model (line 7), which the controller then makes available for the view. The web template `badges/listByGameAndUser.html` then iterates through the badges achieved by the learner using Thymeleaf scripting and formats them using Bootstrap (see code snippet in Listing 4.5).

Listing 4.4: Handling a request for a list of user badges in DashController

```
1  @RequestMapping("/badges/{game}/{userToken}")
2  public String getBadgesByGameAndUser(Model model,
       @PathVariable String game, @PathVariable String userToken)
        {
3
4      RestTemplate rt = new RestTemplate();
5
6      LearnerBadge[] badges = rt.getForObject(apiUrl + "/
           learner/{game}/{userToken}/badges", LearnerBadge[].
           class, game, userToken);
7      model.addAttribute("badges", badges);
8
9      return "badges/listByGameAndUser";
10 }
```

Listing 4.5: listByGameAndUser.html: Displaying a list of user badges for a game with HTML + Thymeleaf + Bootstrap

```
<h4>Badges you have earned</h4>
Note: greyed-out badges have yet to be earned.

<div class="row" th:each="badge : ${badges}">
    <div class="col-md-2 centred badgeRow" th:if="${badge.
        achieved}"><img th:src="@{${'/images/badges/' + badge.
        game + '_' + badge.label + '.png'}}" style="height:70
        px;"/></div>
```

```
        <div class="col-md-2 centred badgeRow" th:if="${not badge.achieved}"><img th:src="@{${'/images/badges/' + badge.game + '_' + badge.label + '_grey.png'}}" style="height:70px;"/></div>
        <div class="col-md-3 badgeRow" style="font-weight:bold;" th:text="${badge.title}">Title</div>
        <div class="col-md-7 badgeRow" th:text="${badge.description}">Description</div>
    </div>
```

Other methods in the DashController class and the Thymeleaf web-page templates exist to handle requests for leaderboards (Figure 4.11), learning progression (Figure 4.9), exercise performance (Figure 4.12) and the main dashboard discussed previously (Figure 4.8).

Figure 4.10: Badges achieved by a user for a game.

The list of badges in Figure 4.10 includes one greyed-out badge, *Speed King*, which is difficult to achieve. It was decided to include non-earned badges in this way to let the learner know that there was an additional badge to be earned. This strategy is designed to communicate high expectations, as per one of the principles of effective teaching practice by Chickering and Gamson (1987), and to assist learners with their metacognition and self-regulation, which are key to a student-centred learning environment (SCLE) (Azevedo et al. 2012)—the concepts of self-regulation and metacognition were expanded upon in Section 2.5.4.

Leaderboard for Challenge: Graph Speed Run

Position	User Token	Time
1	637373	89.101
2	123456	118.532
3	777038	160.934
4	943634	178.736
5	904002	183.058
6	**993482**	**186.604**
7	921252	188.924
8	123586	189.344
9	140432	191.723
10	438810	200.520

Figure 4.11: A leaderboard highlighting the learner's position in comparison to peers.

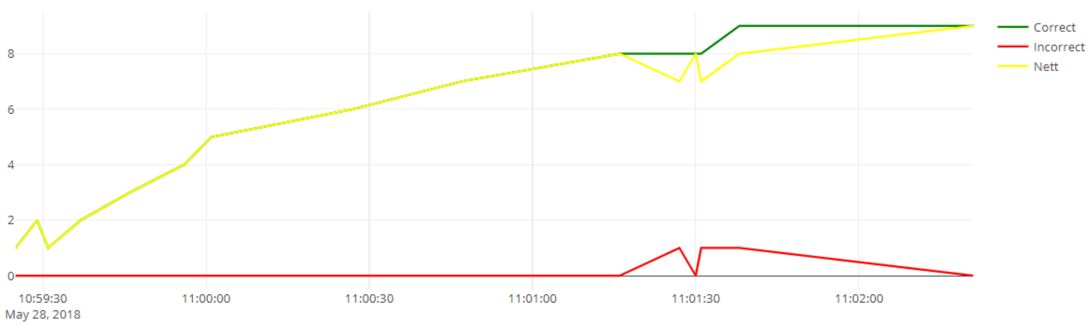


Figure 4.12: Visualization of exercise performance for a learner.

The same can be said, in terms of communicating high expectations, and assisting learners with metacognition, self-regulation and executive functions, of the leaderboard and the visualizations of learning progression and exercise performance.

4.4 The Graph Game

The following subsections provide an introduction to the subject of graph theory, and detail the analysis, design, formative evaluation, and build of the graph game. The remaining steps of the AMDGBL (study, delivery and summative evaluation) are described in Chapters 5 and 6.

4.4.1 A Brief Introduction to Graph Theory

One might legitimately ask: why teach graph theory? This section hopefully sheds some light on why graph theory is fundamental to many things we now take for granted, such as the 'satnavs' in our cars or how Twitter recommends people to follow. This section is intended only to give a flavour of graph theory and why it is such an interesting subject to many and why its visual nature might be suited to the affordances of VR.

Graph theory is a relatively recent area of mathematics (specifically discrete mathematics), dating back less than 300 years, with the first book only appearing in the first half of the 20th century (Chartrand and Zhang 2012). Graph theory is used to model and solve problems in many domains, for example to model molecules, atomic structures and the evolution of species (Cunningham 2018). It can be used to visualize networked computing devices, and by extension can be used to predict how internet viruses might propagate.

Graphs are primarily about relationships. This is obvious in the case of social graphs (or social networks) where people have relationships with people or other objects. For example, to take the example of Facebook, one Facebook user can *friend* another (see Ugander et al. 2011, for a more indepth discussion of Facebook's social graph). Facebook's algorithms can then *recommend* other users to follow based on the concept of *friend of a friend* (if I am a friend of yours, maybe I would like to be a friend of the people you are friends with, because maybe we are all like-minded people with shared interests).

The objects in graphs are known as *nodes* or *vertices* (vertex singular), while the relationships (drawn as lines) between vertices are usually known as *edges*. Figure 4.13 shows a small graph featuring four vertices (three artworks and an art movement, *The Pre-Raphaelite Brotherhood*) and three edges, all showing artworks being part of an art movement (the relationship is *part of*, e.g. the artwork *Beata Beatrix* is in the style of, or *part of*, the *Pre-Raphaelite Brotherhood* movement).

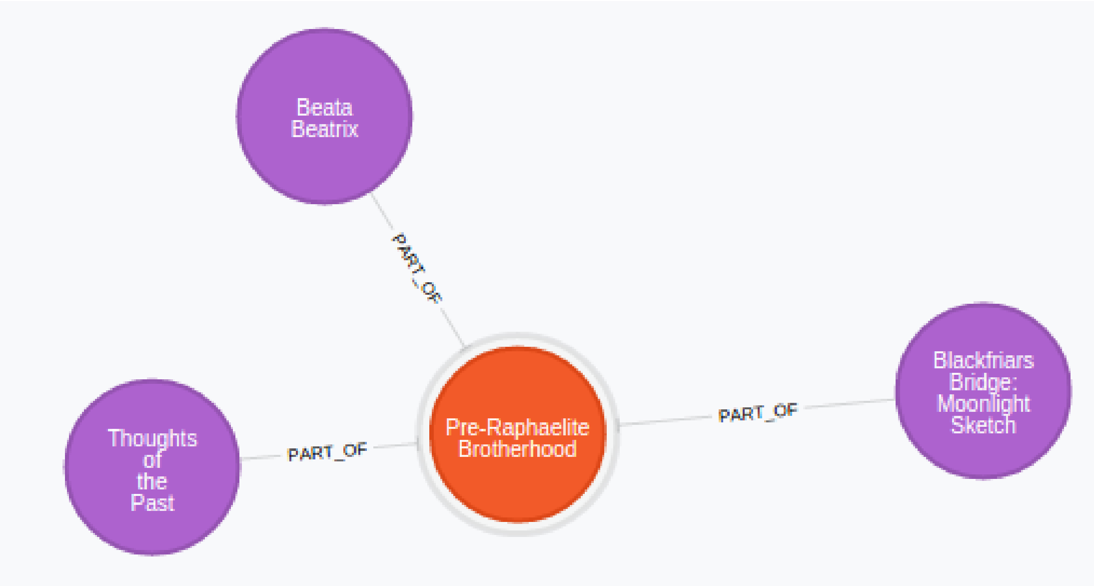


Figure 4.13: A small graph featuring four vertices and three edges.

The edge between two vertices can be bidirectional or unidirectional (in which case an arrow is used instead of a line). Sometimes edges will have weightings to denote some significance to them. An example of using weighted edges would be latency in a computer network; each edge would be a wired or wireless connection with a weighting equal to the average time it takes in milliseconds for a *ping* to travel from a sending computing device and be returned from a receiving computing device (both devices being directly connected vertices in a network graph). Thus, it would be possible to include latency as a factor when calculating the fastest path between two devices on the internet that might be many hops (the traversal from one vertex to another) away from each other.

That is probably as much terminology as a layperson requires to look at a graph and to describe what they see. There is much more to graph theory, including numerous algorithms, such as calculating the shortest path between two vertices (known as Dijkstra's algorithm). If more indepth knowledge is required, the book *A First Course in Graph Theory* (Chartrand and Zhang 2012) is a good starting point.

We can *traverse* relationships to discover how related objects are. In the graph game, the examples and exercises include relationships such as:

- having the same colour;
- species and their subspecies (or vice versa, i.e. subspecies and their parent species);
- read (as in *person read a book*, past tense);
- comes before in a sentence (e.g. the word *is* comes before the word *a* in a particular sentence);
- is a synonym of (e.g. *middle* is a synonym of *centre*);
- forms a well-known phrase with (e.g. the word *colour* forms a well-known phrase, *colour coordinated,* with the word *coordinated*).

To complete this brief introduction to graph theory, an example from the research of the author is presented. The Tate Gallery published a dataset of its artworks and artists in JSON format on GitHub[12] (last updated in October 2014). The author wrote scripts to import the metadata contained in the dataset into a graph database (powered by a Neo4J graph database engine[13]). Those scripts, written in Java and Spring, are publicly available[14].

Figure 4.14 shows a graph visualization of a small subset of the data imported. It shows how two artists, Augustus John and William Johnstone, are related to each other in the Tate Gallery dataset. This relatively minor relationship reveals more than 40 paths between the two artists via their artworks (and the shared properties of their artworks). Taking the example of the abstract type *Subject*, each has painted artworks featuring *hope* (as tagged by the staff at the Tate Gallery). One of the benefits of graphs like this is the potential discovery of previously unknown relationships, or being able to quickly search for all artists who have painted oil paintings featuring ducks, for example. More information about the author's research using the Tate dataset can be found at Cunningham (n.d.).

[12] https://github.com/tategallery/collection
[13] https://neo4j.com/
[14] https://github.com/dlarkinc/tate2neo4j/tree/master/tate2neo4j

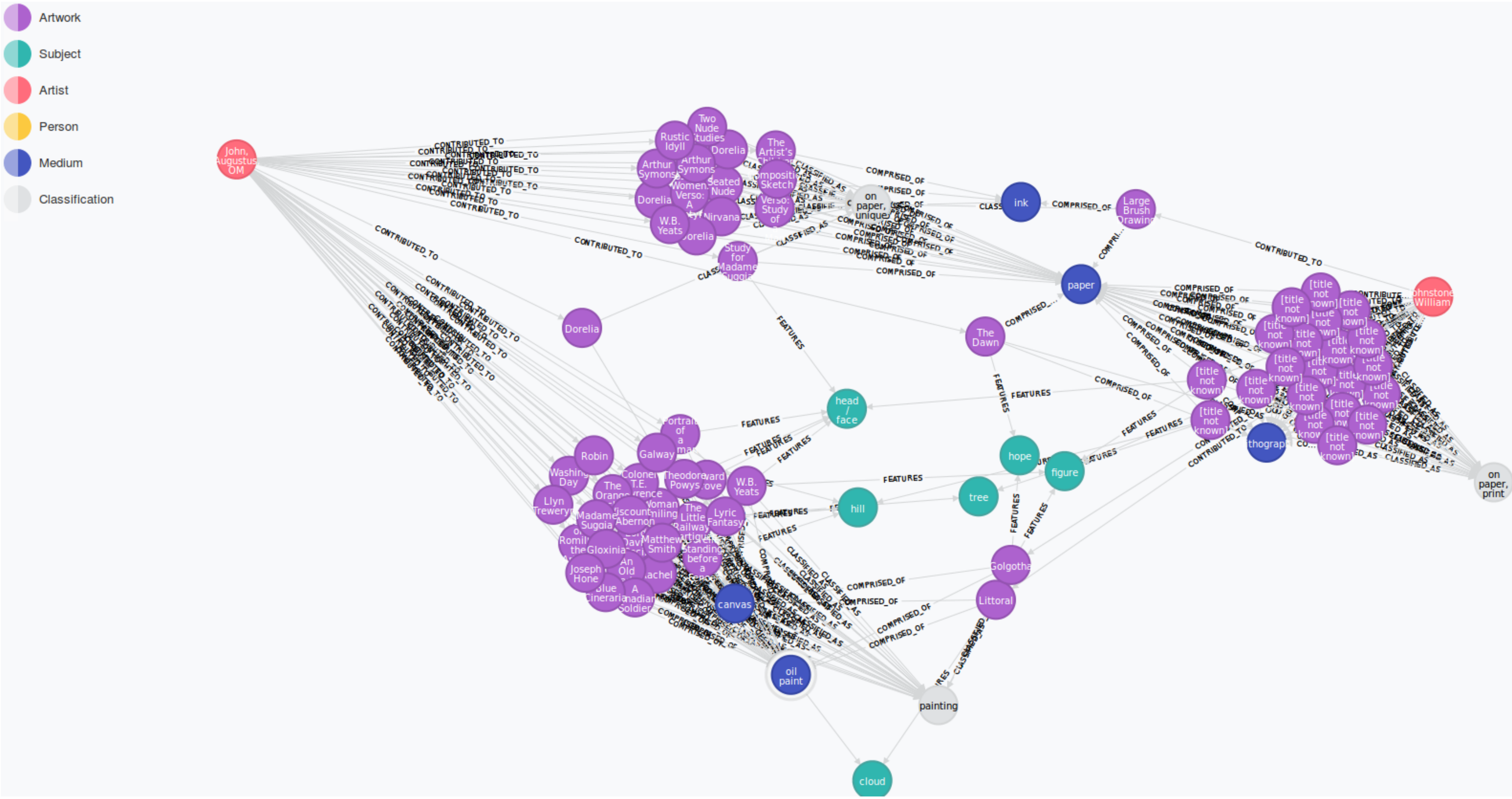


Figure 4.14: A graph based on a subset of the Tate Gallery's dataset of artists and artworks.

4.4.2 The Analysis and Design Phase

4.4.2.1 Needs Analysis

A needs analysis was performed using the 4DF approach discussed in Section 2.3.4.1 to establish the learning context, learner profile and pedagogical considerations.

Learning Context

Cork Institute of Technology (CIT), like many institutes of education, regularly reviews its curricula. Every five years, departments review their programmes of study, revising, removing and adding programmes and modules. These are then validated by external panels of academics and industry experts, and students are consulted during this process.

In the most recent programmatic review completed by the computer science department in 2017, a number of modules included the teaching of the fundamentals of graph theory. The following list includes module titles and the sections of the indicative content related to graph theory.

AI for Sustainability[15] Graph main concepts (sub-graph, path, cycle, connection) and categories (directed, weighted). Modelling real-life sustainability problems as graphs. Graph algorithms: topological sorting, connectivity, minimum spanning tree (Prim's algorithm and Kruskal's algorithm), shortest path (Dijkstra's algorithm), network flow. Travelling salesman problem.

Maths for Computer Science[16] Edges, nodes, graphs, connectedness and valency. Trees, paths and cycles. Eulerian paths and Fleury's algorithm. Hamiltonian paths and Dirac's theorem.

With graph theory spanning modules at undergraduate and postgraduate level, a DGBL solution to teach the fundamentals of graph theory could be useful to ensure a consistent way of teaching graph theory that is reused across modules and from year to year.

There is relatively little in the game-based learning area concerning graph theory. Huang et al. (2017) have developed a gesture-based VR environment for graph visualization, but it does not teach the fundamentals of graph theory,

[15] https://courses.cit.ie/index.cfm/page/module/moduleId/13444
[16] https://courses.cit.ie/index.cfm/page/module/moduleId/13081

nor is it a game. Yang et al. (2016) developed a simple mobile-based game that teaches Hamiltonian paths, which are a particular type of graph. However, the focus of the game is extremely narrow and is not something foundational that could be extended, as is the intention with the graph game of this thesis. Therefore, having searched the literature and performed a more general web search, nothing suitable was found. This meant that developing a bespoke solution was the only way to deliver a suitable digital learning game.

Learner Profile

The *Maths for Computer Science* module is delivered to first-year computer science students. It is also assumed that the postgraduate students taking the *AI for Sustainability* module are encountering graph theory for the first time. Because these are computer science students, they are assumed to be technically adept.

Pedagogical Considerations

A constructivist approach will be taken using the constructive alignment approach of Biggs (1996) to align instruction with assessment (formative only at this point). This means linking the concepts taught to prior experiences. Assessments will be aligned with the concepts taught and will be relevant to what the learner understands about the world.

Scaffolding will be employed, as per Vygotsky's zone of proximal development (1978), so that the learner receives detailed instructions initially, with a tutorial that teaches the game mechanics and dynamics, with simple challenges to try out the game mechanics and dynamics (such as simple graph completion). The learner will progress through partially complete challenges that give the player hints as to how the remainder of the challenge is to be completed, before finally presenting challenges with minimal or no hand holding.

To ensure that learners have an opportunity to experiment and to reflect, Kolb's experiential learning cycle (2014) will dictate the structure of the game. Each level will be constructed as a cycle through concrete experience (a new experience that leverages existing knowledge, such as demonstrating a graph based on their online shopping experience), reflective observation (additional background on the new experience with a chance to pause and reflect), abstract conceptualisation (prompting the learner to think about how the new knowledge might be applied in new contexts) and active experimentation (applying what was learned in the new experience through application of the knowledge in challenges).

The graph game is offered as an accompaniment to traditional teaching methods, such as lectures and slides, rather than a replacement. It is intended to offer choice and to appeal to certain learner preferences, such as kinaesthetic/tactile and visual, but also offer opportunities for reflecting and analysing (see Section 2.5.2).

4.4.2.2 Learning Outcomes

It was noted previously that learning outcomes have their critics. Section 3.3 explained how specifying intended learning outcomes is not mandatory. Referring back to previous sections in the literature review, it also noted that intended learning outcomes are associated with the behaviourist approach (often associated by way of criticism with a managerial approach to education). Therefore, it is important to note that the specification of the intended learning outcomes here is behaviourism in action. However, to add balance to the criticism of many scholars towards this approach, it should be noted that there was always an intention to allow for some emergent learning and that this is supported by an immersive VR environment. The types of learning in the game are discussed in Section 4.4.3.3. These could be bolstered by additional post-game activities, such as individual or group reflection, discussions, brainstorming, and so on. The game itself is intended to encourage reflection of the applicability of what is being learned (given specific real world examples) and to try to imagine other ways in which it could be applied (thus encouraging new and individual ideas to *emerge*). However, the author acknowledges the privileging of these learning outcomes in a behaviourist way in the LAD, particularly when offering learners a visualization of learning progression mapped to a taxonomy. It cannot possibly visualize all of the learning that is taking place.

Following the needs analysis, a number of high-level learning outcomes were devised that would satisfy the fundamental requirements of each module:

1. Demonstrate an understanding of the fundamentals of graph theory.
2. Complete graphs from sets of rules.
3. Apply graph theory fundamentals to real world problems.

There was also a clear objective: the game should be playable in a single lab session—that is, in less than 1 hour—and serve as a taster to demystify the basics of graph theory (excluding complex algorithms, for example).

Bearing in mind the limitations of the objective, the learning outcomes were further broken down:

1. Demonstrate an understanding of the fundamentals of graph theory.
   (a) Understand what a vertex and node are.
   (b) Connect vertices with an edge.
2. Complete graphs from sets of rules.
   (a) Complete a graph according to a simple rule.
   (b) Complete a graph according to a complex rule.
3. Apply graph theory fundamentals to real world problems.
   (a) Manipulate example graphs representing the real world.
   (b) Construct a graph that represents a real world problem.

4.4.2.3 Mapping Learning Outcomes to a Taxonomy

In choosing a taxonomy of learning, both the revised Bloom's and Biggs's SOLO taxonomy were considered. In terms of simplicity for the learner, particularly in terms of visualization, the SOLO taxonomy was chosen.

Once each learning outcome was mapped to the SOLO taxonomy, having considered the level of comprehension required of the learner, the final revision of the learning outcomes mapped to SOLO is presented in Table 4.1.

What should be clear from the final list of learning outcomes, with level of comprehension in brackets, is that there is a progression from uni-structural in 1(a) (such as remembering or defining what a vertex is) all the way to extended abstract in 3(b) (applying knowledge in a new context).

4.4.2.4 Use of MDA Framework

The MDA framework, discussed in Section 2.3.3.1, could be seen as a top-down framework. One could come up with a broad idea for a game and

Table 4.1: Learning Outcomes Mapped to SOLO

1. Demonstrate an understanding of the fundamentals of graph theory. (Multi-structural)
   (a) Understand what a vertex and node are. (Uni-structural)
   (b) Connect vertices with an edge. (Multi-structural)
2. Complete graphs from sets of rules. (Relational)
   (a) Complete a graph according to a simple rule. (Multi-structural)
   (b) Complete a graph according to a complex rule. (Relational)
3. Apply graph theory fundamentals to real world problems. (Extended Abstract)
   (a) Manipulate example graphs representing the real world. (Relational)
   (b) Construct a graph that represents a real world problem. (Extended Abstract)

decide on the aesthetics being aimed for (does one want to frighten, excite, challenge, and so on). This might be true of games designed purely for entertainment purposes, but for the Graph Game, the starting point was the dynamic. Graphs are about connecting things together and following paths. These are quite dynamic in nature. If the game did not feature the ability to connect things together, then the game could never teach the fundamentals of graph theory in an active, engaging way.

The basic ability to connect vertices with edges can be provided by traditional materials, such as pen and paper. A paper-based exercise might contain a rule for how a graph should be completed and a set of vertices. The learner then completes the exercise by drawing the lines to connect related vertices. This basic connection dynamic (D1 below) is the starting point upon which other game dynamics build.

Table 4.2 lists the dynamics broken down into their constituent game mechanics. Only when these fundamental dynamics were listed and broken down could the matter of the game's aesthetics be approached.

One other mechanic alluded to by mechanics D5-2(b) and D5-2(c) is the locomotion mechanic. The player should have the ability to move around in space, for example to move from one end of a graph to another.

The mechanics presented in Table 4.2 read similar to pseudo code. They can

Table 4.2: Graph Game Dynamics and Mechanics

D1 - The graph connection dynamic

1. Fix vertices in space (ignoring gravity)
2. Select a vertex:
   (a) Detect a player's gaze over a vertex
   (b) Handle the *selection button pressed* event:
      i. Highlight the vertex by changing its material
      ii. Store a reference to the selected vertex in memory
3. Connect a vertex to an already-selected vertex:
   (a) Handle the *connection button pressed* event:
      i. Draw an edge (spline) between the vertices
      ii. Update in-memory data structure storing the graph

D2 - The graph manipulation dynamic

1. Grab a vertex with a virtual hand and wave it around
2. Redraw edges frame-by-frame as vertices are moved

D3 - The graph solving dynamic

1. Store graph solution in memory
2. Check the current graph frame-by-frame against the solution
3. Inform the player about how many edges are correct versus incorrect:
   (a) Count number of correctly-connected edges
   (b) Count number of incorrectly-connected edges
   (c) Update text in display area with counts
4. Use a different material (for example, a red one) to draw incorrect edges

D4 - The instructions dynamic

1. Add text object to multiple walls (so it is visible when player turns around)
2. Change text when event occurs:
   (a) Handle *next button pressed* event and move to next instruction
   (b) or, update text with next instruction when assigned task is completed:
      i. Play ding sound to indicate task has been completed

D5 - The game progression dynamic

1. Load new level
2. Within level:
   (a) Wall off areas (examples, challenges)
   (b) Add teleportation pad with trigger box
   (c) Move player to new location when trigger box collided with (i.e. the player teleports onto the teleportation pad)

D6 - The reward dynamic

1. Contextual code that checks if condition for reward has been met
2. Play a chime sound
3. Display image (badge) in instructions display area

be made more specific once a game engine has been chosen. A 2D game engine would handle locomotion in a very different way than would a 3D game engine capable of rendering an immersive VR environment. The choice of game engine and how some of the game mechanics were implemented are discussed in Section 4.4.4.1.

The final act is to decide on one or more aesthetics. Schell (2015) states that it is not the game that is the experience—the game **enables** the experience. The game helps create sensations at the psychological level. The authors of the MDA framework do not claim that their list of eight aesthetics is exhaustive. The design of the graph game arguably features the following from the MDA aesthetics list:

Challenge The game was designed to gradually increase the level of challenge as the game progressed. Beginning with simple tasks, such as selecting a vertex and then connecting two vertices together, the game culminates with a timed challenge.

Fellowship The platform was designed so that players could compare their performance in challenges to other players. Other social features were planned, but not implemented, such as real-time alerts when other players achieved badges or set high scores.

4.4.2.5 Mapping Learning Mechanics to Game Mechanics

To map intended learning to game mechanics, the LM-GM model (see Section 2.3.4.3) was used. Figure 4.15 shows the high-level structure of the game. The game begins with a tutorial to teach the player about the game's mechanics, such as *gazing*, *selecting a vertex*, *grabbing a vertex* and *connecting vertices*.

Once the player has demonstrated an ability to execute the game's mechanics, the game moves to a repeating levels structure. Each level begins with a briefing as to the purpose of the level. This is followed by a series of instructions, including conceptual information. As the player carries out certain actions, achievements (badges) will be awarded. A challenge will be presented to the player and feedback will be given as a player attempts to complete the challenge (sometimes against the clock). The player will be instructed as to the relevance of the new knowledge and will be given an opportunity to pause, play around with a graph and reflect as to its relationship to their own prior experience. Once the game is complete, the player can view statistics about performance, badges earned and learning completed in relation to overall learning objectives.

Table 4.3 maps each of these game elements to the learning mechanics and game mechanics of the LM-GM model. Section 4.4.4.2 discusses how these mechanics were implemented using Unreal Engine 4.

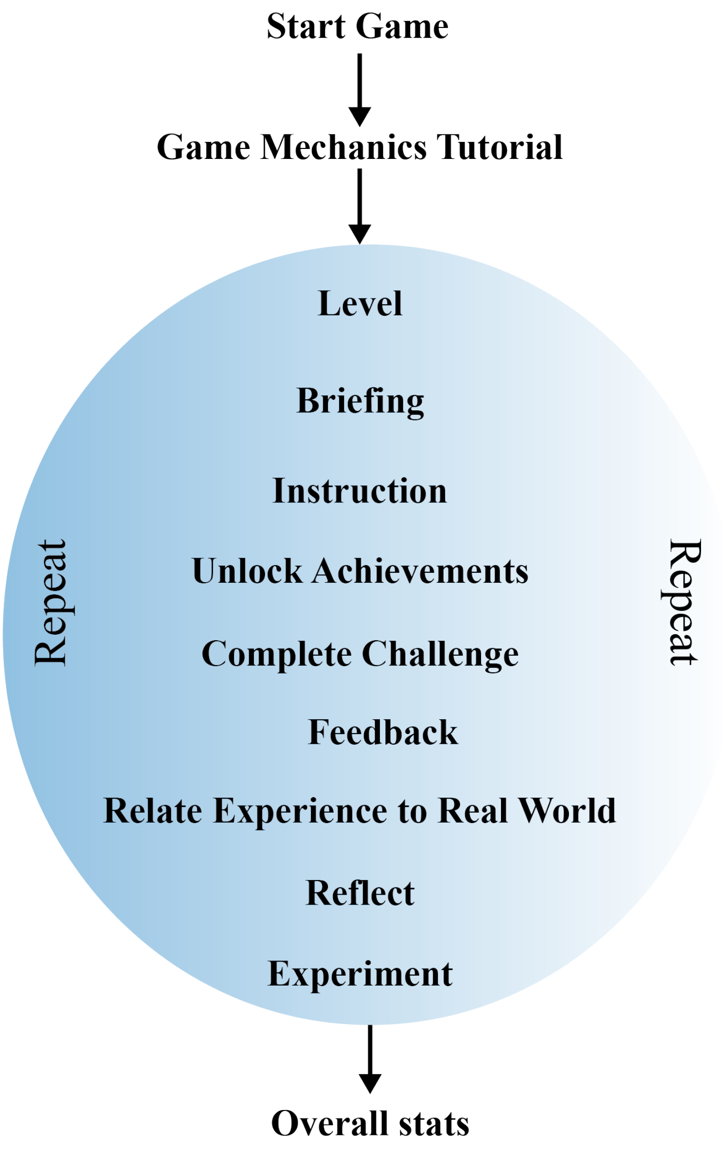


Figure 4.15: High-level structure of the graph game.

Table 4.3: Mapping learning to game mechanics

Game Element	**Learning Mechanic**	**Game Mechanic**
Game Mechanics Tutorial	Instructional, Guidance, Action/Task, Feedback, Simulation	Tutorial, Movement, Simulate/Response, Goods/Information
Level		Levels
Repeat	Repetition	Behavioural Momentum
Briefing	Instructional, Guidance	Cut Scenes/Story
Instruction	Instructional, Guidance	Cascading Information
Unlock Achievements	Motivation	Rewards/Penalties, Status, Competition
Complete Challenge	Action/Task, Feedback, Plan, Hypothesis, Modelling, Competition, Assessment	Movement, Time Pressure, Pavlovian Interactions, Feedback, Assessment, Urgent Optimism, Status
Feedback	Feedback	Feedback
Relate Experience to Real World	Realism, Instructional, Observation	Goods / Information, Cascading Information
Reflect	Reflect/Discuss	
Experiment	Experimentation	Movement, Design/Editing, Simulate/Response
Overall Stats	Analyse, Reflect/Discuss, Ownership, Accountability, Responsibility	Status, Ownership

4.4.2.6 Additional Gamification Features

Badges, leaderboards and points (or levelling up) were discussed in Section 2.3.3.3. Based on a review of the literature on badges, it was apparent that while there can be mixed outcomes with the use of badges, when they are carefully designed and integrated they can have a positive effect. The same can be said of leaderboards. It was decided to integrate both badges and a leaderboard into the graph game.

When weighing up whether to include points or levelling up in the graph game, it was decided that the visualisation of learning outcomes mapped to the SOLO taxonomy is a very similar game element—going through the taxonomy from a pre-structural up to an extended abstract level of comprehension is a form of levelling up. In addition, some of the badges include a level to indicate progress. Therefore, the accumulation of points was not implemented.

4.4.2.6.1 Badges

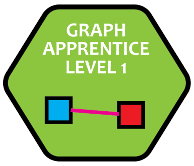
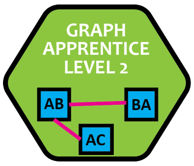
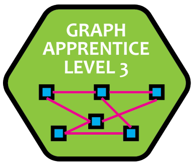
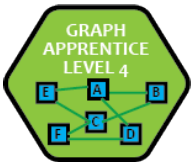
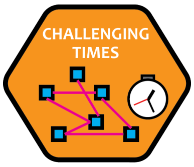
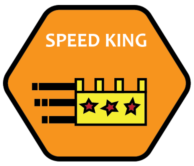
Six badges (listed in Table 4.4) were designed to reward players for making progress or completing challenges in the game. Four of the badges were grouped under the title of **Graph Apprentice** with an achievement level appended, for example **Graph Apprentice Level 3**. This gives a clear indication to players that they are levelling up as more is learned about graph theory.

Two more badges were added for the final timed challenge—one given for completing the challenge regardless of time, and the other only awarded when the challenge completion time was under ninety seconds. The **Speed King** badge was clearly signposted—before beginning the final timed challenge, the instructions include: “If you beat 90 seconds you will get the Speed King achievement.”

4.4.3 Formative Evaluation of the Game and Platform Design

The following subsections represent a formative evaluation of the game and platform design as per Section 3.6. Additional formative evaluation was

Table 4.4: Badges in The Graph Game (images drawn using Adobe Illustrator)

Image	Title	Description
	Graph Apprentice Level 1	Learn about graphs, vertices and edges and connect 2 vertices together
	Graph Apprentice Level 2	Complete a graph according to a simple rule
	Graph Apprentice Level 3	Partially complete a graph according to a more complex rule
	Graph Apprentice Level 4	Complete a full graph according to a more complex rule
	Challenging Times	Complete the timed graph exercise
	Graph Speed King	Complete the timed graph exercise in under 90 seconds

performed at the end of each sprint and study, as detailed in the learner study (Section 5.3).

4.4.3.1 Flow and Balance

Flow and balance were discussed in Section 2.3.3.2, with Csikszentmihalyi's dimensions of flow and the flow channel (Figure 2.1) used as guidance while designing the challenges and Schell's lens of challenge (Table 2.4) identified as a relatively quick evaluation tool to ask if the game is balanced between the level of challenge and player skill. The table of mapped flow and game elements (Table 2.3) is a more detailed framework for the evaluation of flow. The use of each to evaluate the graph game's design from the flow and balance perspective is discussed in this section.

When designing the game's challenges, the flow channel was always in mind. For example, when designing the final timed challenge, the timer was introduced for a number of reasons, but one of them was *novelty* (which corresponds with the challenge axis in Figure 2.1). A player might start to get bored playing the same type of challenge again, but the introduction of the timer, and the promise of a badge by completing the challenge within ninety seconds, along with the leaderboard, introduced an extra level of novelty. In addition, *learning* corresponds to the skills axis, and the tutorial level allowed learning to progress at a rate that matched the increase in challenge.

Schell's lens of challenge is used in Table 4.5 to assess whether there is balance in the game. According to the analysis, the game should be successful in delivering challenges that increase as the player's ability or knowledge increases.

Table 4.6 uses the table of mapped flow and game elements (see Table 2.3). The gameplay elements of Pavlas and Cowley et al. provided guidance when pointing to elements of the graph game that support each of the flow elements.

The evaluation of balance and flow performed suggests that the graph game's design will gradually build the player's skills level at a pace that is appropriate for the increase in challenge. The introduction of novelty as the challenges progress should keep the player from getting too anxious.

The structure of the game into levels with breaks in between, where the player is informed about badges earned and time is allowed to survey the environment and become familiar with the upcoming challenge, allows for the peaks and troughs of dramatic tension (as per the wavy line through the flow channel in Schell's modification of the dimensions of flow in Figure 2.2).

4.4.3.2 Motivation

The game's motivational affordance was evaluated using Schell's lenses of motivation (see Table 4.7) and novelty (see Table 4.8). The balance in terms of intrinsic and extrinsic motivations that support each other, and elements of novelty that are maintained or which do not entirely define the game, point to

Table 4.5: Evaluation of Game Using Lens of Challenge

What are the challenges in my game?

In the tutorial level, there are micro-challenges, such as selecting a requested vertex and making a simple connection. The first significant challenge is the completion of the colour graph. The next significant challenge is to complete a graph in level two according to a more complex rule: a taxonomic hierarchy of animal species. The next significant challenge is to complete a word graph according to a rule—synonyms and phrases—under time pressure.

Are they too easy, too hard, or just right?

The tutorial level increases player skill, teaching about the fundamentals of graphs and getting the player familiar with the controls and mechanics of the game. The micro-challenges and the colour graph challenge are easy, but appropriate for a tutorial level. The taxonomy and word graph challenges are at an appropriate level, given that the player first completes a graph under no time pressure and then completes one with a time pressure.

Can my challenges accommodate a wide variety of skill levels?

The adherence to the UDL framework helps to ensure that as many players as possible can access the game. The intended audience is computer science students, so the variety of skills should be quite narrow compared to the general population. The gradual increase in challenge should allow the majority of players increase their skill levels to keep pace with the increase in challenge.

How does the level of challenge increase as the player succeeds?

As discussed under the other questions, the challenge ramps up from single-task micro-challenges, through simple challenge, to complex challenge, to timed complex challenge.

Is there enough variety in the challenges?

The challenges are all about completing graphs, but the rules governing completion of the graphs changes—colours, taxonomy, words. The addition of a timer to the final challenge adds an additional novelty to it.

What is the maximum level of challenge in my game?

Players must complete a graph according to a rule with two elements to it. Players must look for both synonyms and phrases. This is done under time pressure to try to achieve a badge and to place as high as possible on a leaderboard.

Table 4.6: Elements of Flow Mapped to Game Elements in the Graph Game

Flow Element	Elements of Graph Game Design
(1) A task to be accomplished	Player is made aware that the game is teaching the fundamentals of graph theory.
(2) The Ability to concentrate on a task	The use of VR is immersive, including virtual hands and the ability to manipulate graphs physically.
(3) Sense of control over actions	Player locomotion and ability to manipulate graphs with hands allows great amount of agency; controls are introduced slowly and should be intuitive; controls are minimal to avoid confusion.
(4) Deep but effortless involvement	Game is offered as a choice compared to traditional teaching methods; player can focus on the task at hand with challenges that increase with their skill; real-world examples make what is being done relevant and therefore more motivating.
(5) Clear task goals	Purpose of tutorial is clear; instructions and rules on walls make clear what is to be done; the web-based dashboard also provides a clear listing of learning outcomes / objectives.
(6) Immediate feedback	Correct versus incorrect counts displayed on wall; green edges for correct, red for incorrect; timer for the final challenge and achievement or non-achievement of speed king badge.
(7) Being less conscious of the passage of time	VR helps with immersion and time seems to pass quickly, but only playtesting will confirm this.
(8) The sense of identity lessens, but is reinforced afterwards	The game does not feature a player avatar, so lessening of identity seems unlikely, but there will be a sense of achievement if the speed king badge is achieved, challenges are solved and a good time is viewed on a leaderboard.

a game that should be successful from a motivational standpoint.

Table 4.7: Evaluation of Game Using Lens of Motivation

What motivations do players have to play my game?

The players need to learn graph theory and the game offers potentially a more interesting and engaging way of learning about the subject. It also offers them an opportunity to revise what was learned in class and to do it at a time that suits them at a location of their choice.

Which motivations are most internal? Which are most external?

Intrinsic motivation will be driven by an inner desire to learn and master the fundamentals of graph theory. For some learners, it will suit their learning preferences and make the difference between pass or fail. The external motivators include the badges and leaderboard, but also the desire to perform well in the challenges against peers.

Which are pleasure seeking? Which are pain avoiding?

In terms of pleasure seeking, the game borders on simulation rather than being a game; but it is rescued from the simulation label by the innovative challenges, which are varied. With some modifications, such as having randomized challenges, the graph game would be even more *gamelike*. In terms of pain avoidance, graph theory is an interesting subject for some, but will be a chore for others. Making the learning fun, primarily through interesting challenges, should avoid the learning pain for some.

Which motivations support each other?

The intrinsic motivation to learn is supported by the extrinsic motivation to perform well in challenges (resulting in badges or elevation of status amongst their peers).

Which motivations are in conflict?

There appear to be no obvious conflicts.

4.4.3.3 Mapping of Learning to the Game

Section 4.4.2.5 mapped the learning mechanics (LMs) to game mechanics (GMs). An analysis of the learning mechanics in Table 4.3 seems to support the pedagogical considerations outlined in Section 4.4.2.1. Table 4.9 details how the LMs and/or GMs support each of the considerations.

The analysis suggests that the game will be successful from a serious game mechanic perspective.

Table 4.8: Evaluation of Game Using Lens of Novelty

What is novel about my game?
It uses VR, which most students have not encountered. It offers a hands-on and visual way to learn about a mathematical subject.
Does my game have novelties throughout or just at the beginning?
The 'wow' factor of VR will wear off after a certain amount of time. The ability to manipulate graphs in an immersive 3D environment should not.
Do I have the right mix of the novel and the familiar?
There appears to be a good mix of novel, as outlined above, and familiar, such as traditional instruction with text.
When the novelty wears off, will players still enjoy my game?
The 'challenge' aesthetic should keep players enjoying the game—the exercises are varied.

Table 4.9: Mapping of Learning to the Game

Experiential Learning Cycle	*Repetition* occurs, indicating a cycle. LMs such as *Action/Task*, *Realism* and *Simulation* suggest that a concrete experience is had. *Reflect/Discuss* and *Observation* suggest that reflective observation will occur. *Hypothesis* and *Analyse* suggest that abstract conceptualisation happens. *Plan*, *Modelling* and *Experimentation* point to active experimentation.
Scaffolding	*Guidance*, *Cascading Information* and *Feedback* suggest that learning will be scaffolded.
Learning Preferences	*Movement*, *Modelling* and *Action/Task* suggest the game will appeal to tactile/kinaesthetic learners. *Reflect/Discuss* and *Analyse* suggest the game will have elements that suit the reflecting and analysing preferences. *Simulation* and *Modelling* may suit visual learners.
Constructive Alignment	*Assessment* aligned with *Instructional*, *Feedback* and *Observation* suggest the game will be constructively aligned.

4.4.3.4 Narrative

A narrative was not included in the graph game. However, the positive benefits of narrative, as discussed in Section 2.3.3.4, suggest that the game could have benefited from a narrative (and story, characters, and so on). This deficit is discussed in Section 6.4, which addresses future work that could be carried out.

4.4.3.5 Universal Design

While it would be best practice to evaluate the design of the game and platform from a UDL perspective prior to any implementation, this did not occur. Instead, the evaluation was carried out after the initial prototype and study were completed. A disadvantage of this approach was that some avoidable issues were encountered, such as problems reading text (that could have been addressed with an audio option), that might have been foreseen and addressed. Section 4.5 performs an analysis of the game and platform from a UDL perspective and reflects back on what might have been discovered at this post-design / pre-implementation phase.

4.4.4 The Build Phase

4.4.4.1 Choice of Game Engine

A *game engine* is a term that originated in the mid-1990s when games like *Doom* began to have a clear separation of reusable core components, such as 3D rendering and collision detection, from the individual game elements, for example, art assets and the rules of play (Gregory 2014). This means that game engines are platforms that can be reused for multiple games.

Prior to settling on VR as the medium for the graph game, when still in the literature review and exploratory phase, a number of prototypes were developed on a number of game engines. This included:

- a 3D third-person perspective game in *Unreal Engine 4*[17] (as discussed in Cunningham 2016b). Figure 4.16 shows one feature of the game, dynamic dialogue trees.

[17]https://www.unrealengine.com

- a 2D top-down RPG (role-playing game) in *GameMaker Studio 2*[18].
- a text-based interactive story in *Twine 2*[19]. It is based on the "William" pedagogical case described in Chambers et al. (2014). Figure 4.17 demonstrates how the game offers choices that affect future outcomes.
- a 2D platformer in *Unity 5*[20].

Figure 4.16: A serious game to dissuade adolescents from taking performance enhancing drugs.

For an individual developer to create a VR game without using a game engine would be almost impossible. VR is supported only by a small number of game engines. Based on the exploratory research carried out, two game engines were short-listed: Unreal Engine 4 (UE4) and Unity 5. Both offer support for VR, both are free to use for non-commercial use and both have been used to develop a wide range of VR content. Ultimately UE4 was chosen because of the researcher's personal preference and greater experience of using it extensively during the exploratory research phase and teaching game development using

[18]https://www.yoyogames.com/gamemaker
[19]http://twinery.org/
[20]https://unity3d.com/

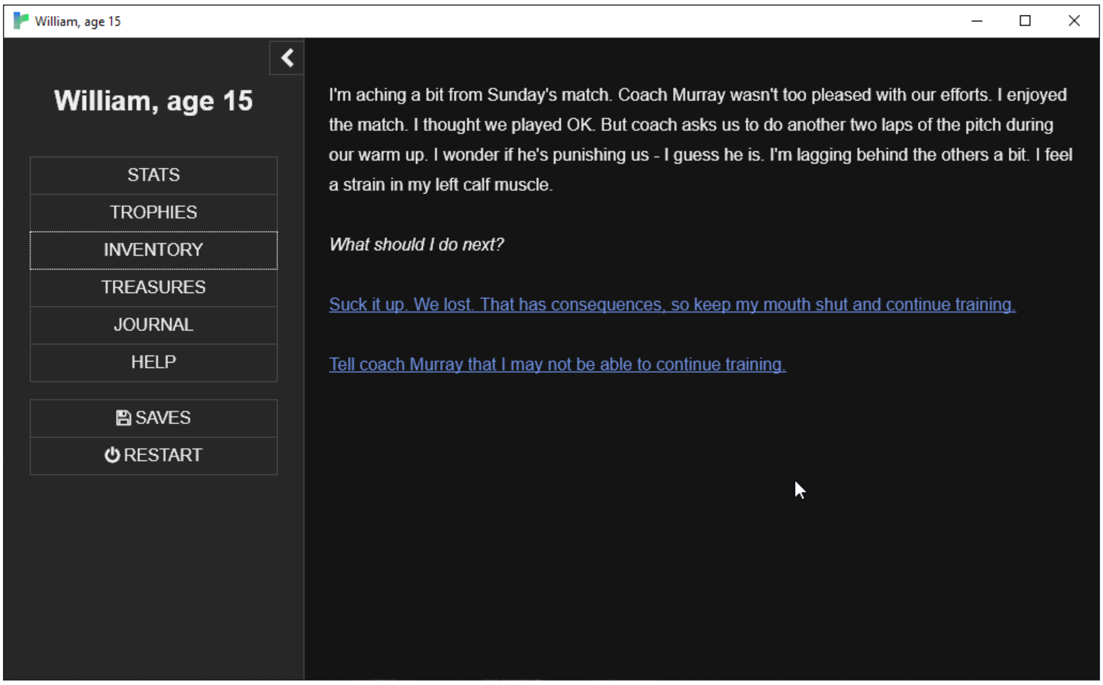


Figure 4.17: A text-based role-playing game prototype built using Twine 2.

it. UE4 provides a VR template, which is essentially an empty world with functioning teleportation for locomotion and the ability to grab and lift objects—everything beyond that needs to be implemented by the developer. An additional benefit was the intuitive Blueprint visual scripting language; rather than writing code as text, code is written visually using a drag-and-drop mechanism to connect nodes using the visual metaphor of a breadboard (in the electronic engineering sense of the word) and its pins and wires.

Figure 4.18 shows an example Blueprint script from the exploratory research phase. It is the equivalent of a number of *if statements*, *logic operations* and *variable assignments* that can be found in traditional high-level programming languages such as C and Java. The example Blueprint script is the equivalent of about six programming statements (three ifs / branches, two assignments and one while loop).

UE4 is object-oriented, allowing for game objects to be easily reused or extended to add additional context-sensitive functionality. More about UE4 and Blueprints is available in the official documentation[21].

[21]https://docs.unrealengine.com/en-us/Engine/Blueprints

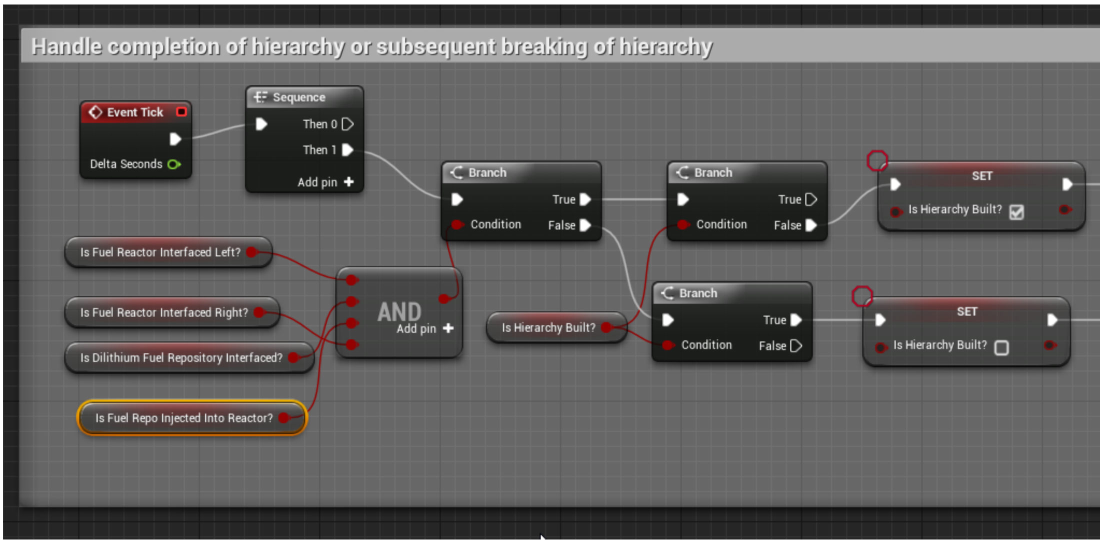


Figure 4.18: Example of Blueprint visual scripting in UE4.

4.4.4.2 Implementation of Game Mechanics

This section features a list of notable game mechanics (as described in Table 4.2) and how they were implemented using Unreal Engine 4. Each mechanic contains one or more references to the table; for example D1.2(a) is the gaze mechanic (described as "Detect a player's gaze over a vertex" in the table).

A number of buttons on the Oculus touch controllers are referenced. Figure 4.19 shows a top down view of the left and right controllers. On both controllers a thumb stick (marked as T) can be pressed / clicked and directed through 360 degrees. The first study went through iterations that finally ended up mirroring A with X to ensure left and right controllers were fully mirrored (informed by UDL). The B button had a limited use in the first study iteration (showing and hiding floating messages), but was removed for the other iterations due to findings from item H2 in the learner study questionnaire (iteration 1 version). For more on the iterative nature of the studies and the findings from the questionnaire administered, see Section 5.3.

The grip (G) and trigger buttons were mirrored prior to the first study iteration beginning. Figure 4.20 gives a better view of the trigger and grip buttons, as well as showing the infra-red lights emitted for tracking purposes (buttons are outlined for clarity). The grip button is pressed with the middle finger, the trigger button with the index finger, and the thumbs are used for the thumb stick, A, B, X and Y buttons.

Figure 4.19: Top view of Oculus touch controllers

Locomotion

The locomotion mechanic is fundamental to all dynamics. For graph connection, manipulation and solving, the player will often need to move to a new position to get a better view angle or to get close enough to a vertex to select it. As discussed in Section 2.4, VR sickness can be an issue for many when free movement is allowed. Therefore, to avoid this issue, a teleport mechanic was used. UE4 is shipped with a VR template that includes teleportation and this was used.

Figure 4.21 shows a beam extending from the hand in an arc, then hitting the ground where an arrow indicates where the player will be positioned and in what direction the player will face once teleportation is complete. The arc is drawn by first simulating a ball throw, storing the path, then using it to draw the teleportation beam arc.

Audio

References: D4.2(b), D6.2

Audio is used in two ways in the game. The first is to alert the player to the completion of a small task during the tutorial level. This was added for the final iteration when observations showed occasional lack of awareness that a

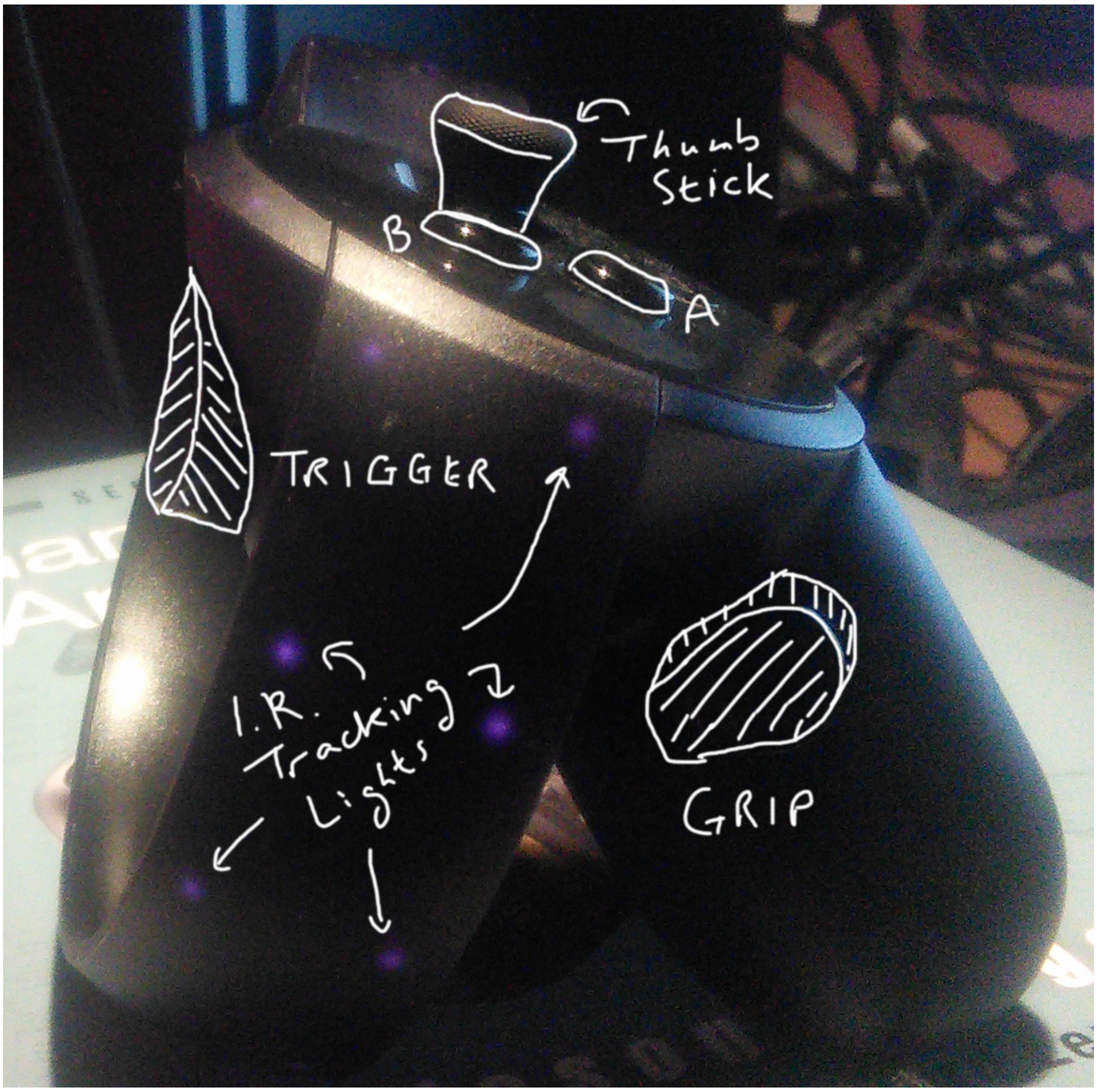


Figure 4.20: Side view of right Oculus touch controller

task had been completed. A simple ding sound was used. The second is to alert the player to the award of a badge (simultaneous to the badge being displayed in the instructions box). A fanfare / ta-da sound was used.

Gazing

References: D1.2(a)

The gaze mechanic is used when selecting vertices. A small white ball is rendered a few metres from the player camera. This gives it the appearance of an aiming dot similar to a dot in some rifle scopes. When the ball is rendered behind another object it changes to red.

As Figure 4.22 shows, a hidden line trace is plotted from the player camera to

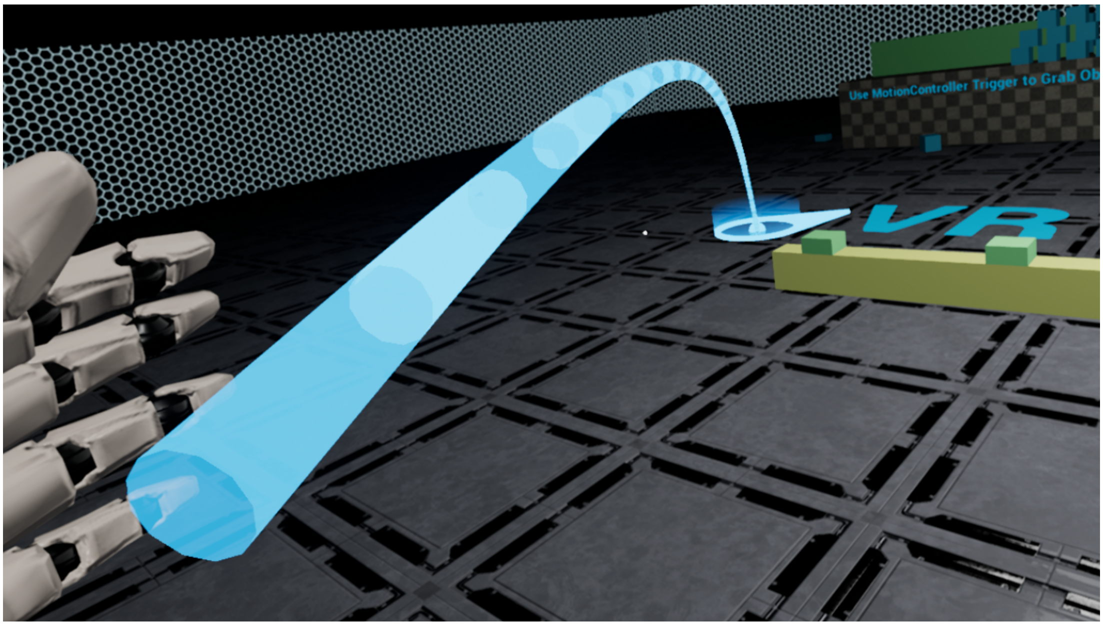


Figure 4.21: Teleportation beam arc and arrow

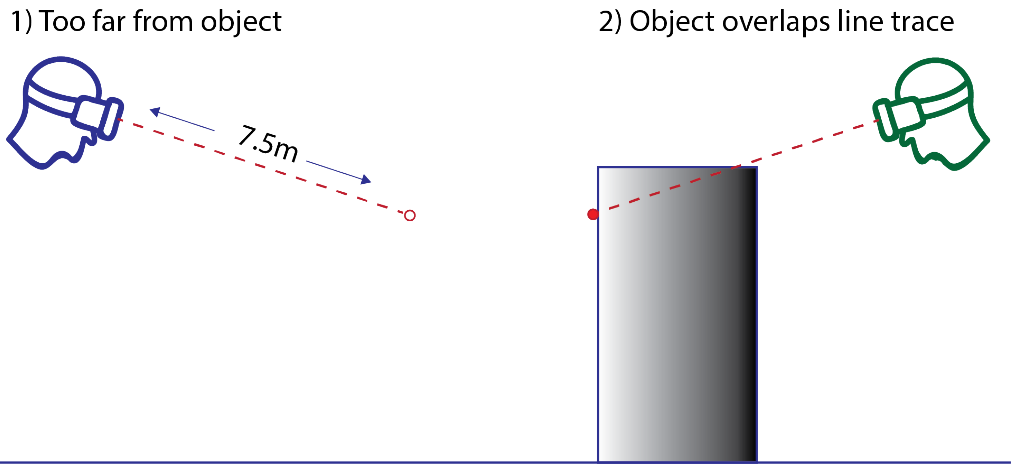


Figure 4.22: Design of the gaze mechanic

a point 7.5 metres directly in front of the player's gaze. The small sphere is also drawn 7.5 metres from the player camera so that its position coincides with the end of the line trace. UE4 static mesh components can be configured to be rendered in what is known as a custom depth pass[22], which allows outlines of objects to be drawn even when they are behind other objects (at a lower depth). In the case of the aiming dot, this makes it red when behind another object.

[22]https://docs.unrealengine.com/en-US/Engine/Rendering/PostProcessEffects/PostProcessMaterials

A plugin for Unreal Engine 4, *Virtual Reality Pawn and Components*[23], was purchased and the RunebergVR_Gaze component added to the player pawn camera component (see Figure 4.23). As play begins, the gaze range is set to 750 cm and the gaze target duration to 0.2 seconds (meaning a gazeable object will register a gaze detection after it has been continuously gazed at for at least 0.2 seconds). Objects can be set to *gazeable* or *non-gazeable*; where non-gazeable, the line trace will not detect a collision with it and will pass through to the next object behind it. The first study iteration showed that the orginal 5 metre trace length was too short and it was lengthened.

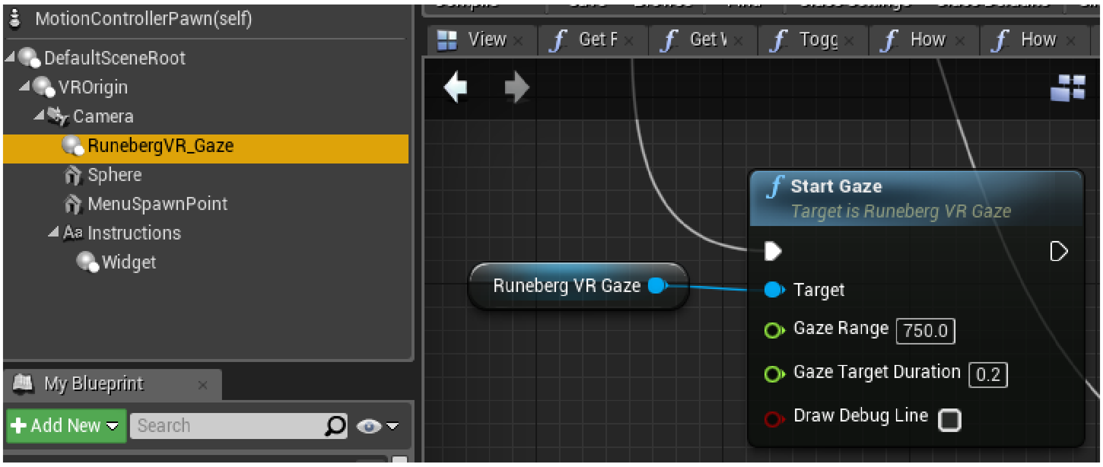


Figure 4.23: RuneBergVR Gaze Component

Grabbing

References: D2

The grab mechanic was part of the UE4 VR template. With a virtual hand overlapping a grabbable object, the player can press and hold the grip button on the Oculus touch controller. A closed virtual fist and a brief haptic feedback (mild rumble / vibration) on the controller lets the player know a vertex has been grabbed. With the grip button held down, the player can wave the grabbed vertex around (see Figure 4.24). It is also possible for players to teleport while grabbing a vertex to take it with them, and even to grab two vertices at the same time and to teleport with both.

An added complication is that when a vertex is grabbed and moved, not only does the vertex get re-rendered in each frame automatically by UE4, but the edges connected to it need to be redrawn manually—otherwise the vertex

[23]https://www.unrealengine.com/marketplace/vr-pawn-components-plugin

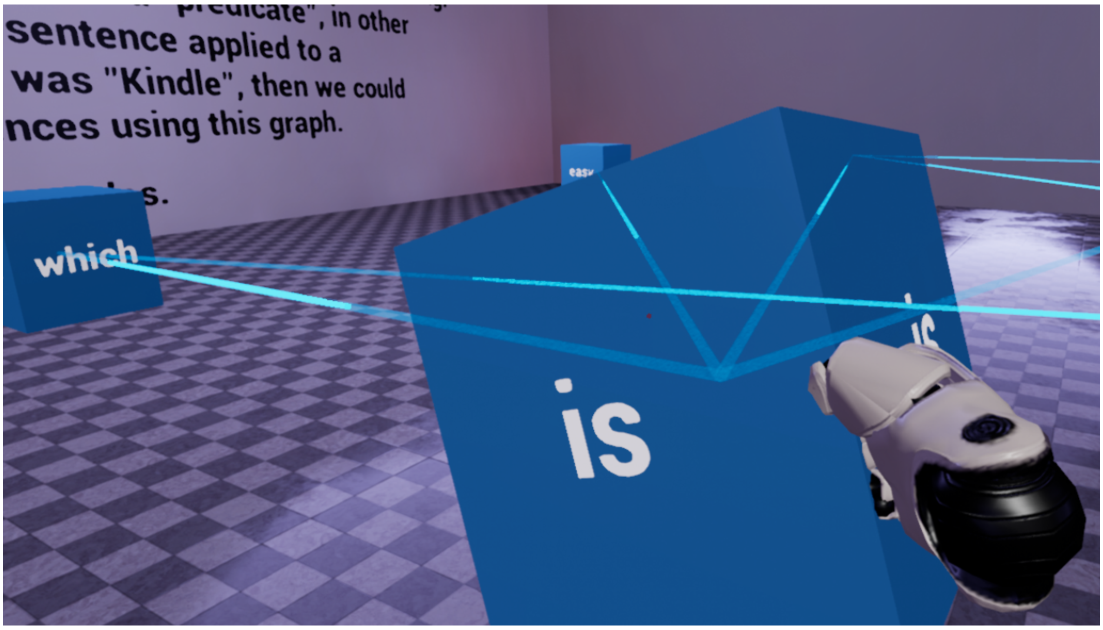


Figure 4.24: Grabbing a Vertex

would move, but the edges would not move, the vertex would be connected to nothing, and there would be dangling edges.

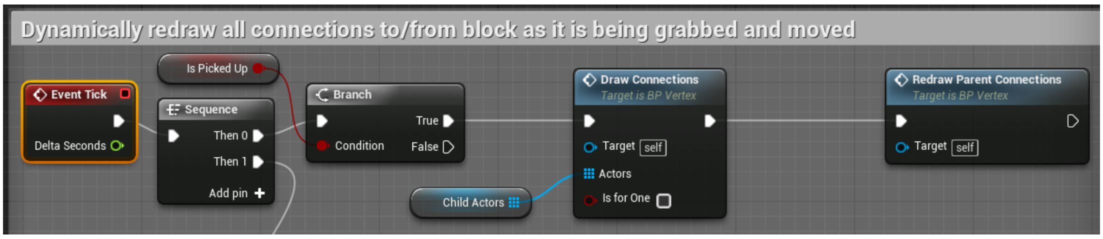


Figure 4.25: Blueprint script that redraws all edges connected to a grabbed vertex

While this section would become cluttered very quickly with a lot of Blueprint script examples, it is worth showing a sample to illustrate the complexity of this aspect of connecting and grabbing vertices. Figure 4.25 is a snippet of Blueprint script from within the vertex class. It illustrates that for every tick of the game (as soon as the game loop does all physics calculations, rendering, and so on, it immediately moves to the next iteration of the game loop, even if the graphics card did not have time to draw the frame) the *isPickedUp* status of the vertex is checked and if it is in a picked-up state (that is, it is currently being grabbed), all of the edges connecting the vertex to its children, and all of the edges to its parents' vertices, will be redrawn. This check is performed within every vertex, so when two vertices are grabbed, both will simultaneously redraw all of the edges connected to them.

Connecting Vertices and Drawing Edges

References: D1

Connecting vertices is a dynamic comprised of several mechanics. Gazing, which has already been discussed, is used in conjunction with the trigger button to select a vertex. With one vertex selected, the player can gaze at another and press the A button to toggle a connection between the vertices.

When that event occurs, a number of algorithms and data structures are employed to update the composition of the graph being solved. A hierarchical data structure of child and parent vertices is updated and the edge is drawn (if making a connection) or deleted (if disconnecting).

4.4.4.3 Implementation of Game Structure

An overarching structure was prototyped as part of the LM-GM analysis in Section 4.4.3.3. This section provides detail on how the structure was implemented in the game with screengrabs to illustrate some of the points. This section also highlights how and where the learner interaction events were embedded (the final step in the analysis and design phase illustrated in Figure 3.3). As noted previously, the structure was designed with reference to the pedagogical considerations noted as part of the analysis and design phase. This includes learning preferences, experiential learning cycle and scaffolding.

Figure 4.26 shows the game structure and flow (from left to right, top to bottom). Not every minute interaction can be diagrammed (for example, some components in the structure require multiple instructions or send additional learner interaction events to the API). The following subsections explain the components of the game structure.

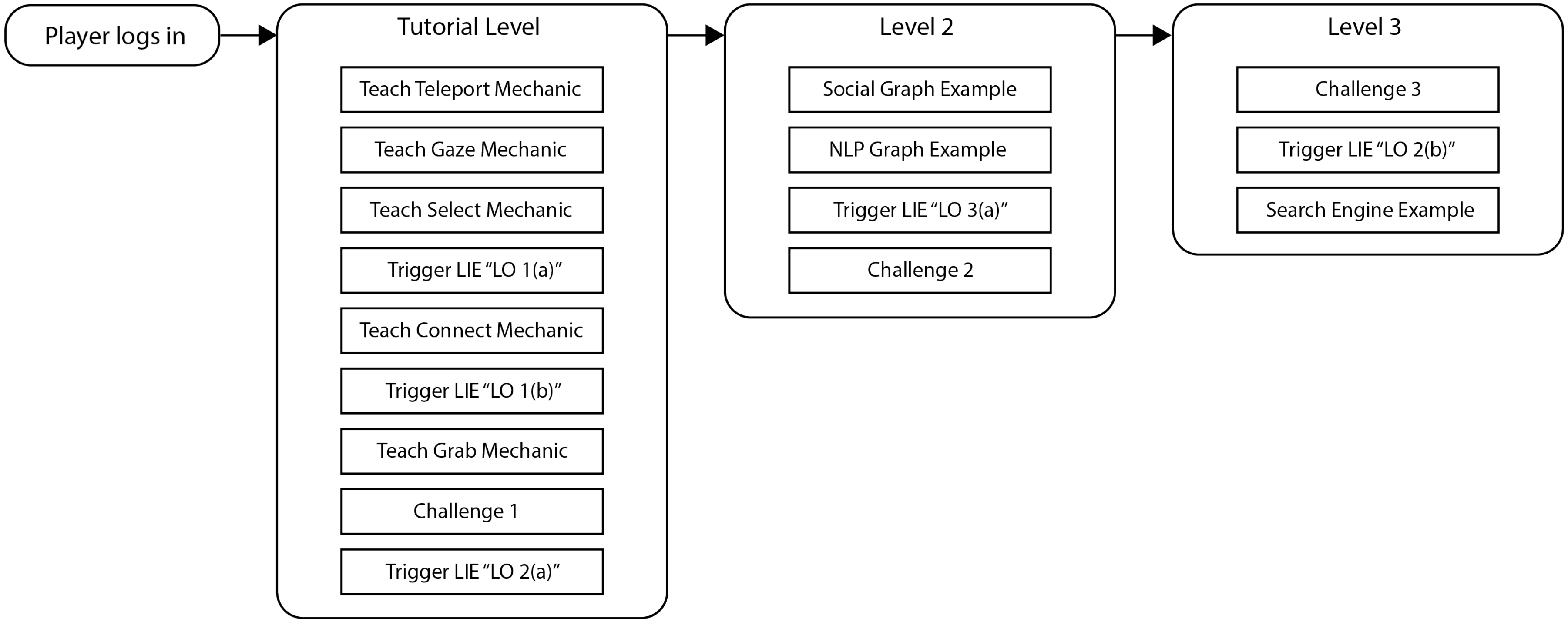


Figure 4.26: Game structure broken down into components.

Player Logs In

When the game loads, the player must enter a code into the keypad shown in Figure 4.27. This sends a communication to the central API to verify that the player's code is registered to the game. If the learner-game registration does not exist, a message appears in the keypad to let the player know the code was incorrect. Otherwise the player continues with the tutorial level and the learner interaction event (LIE) "tutorial_start" is sent to the API.

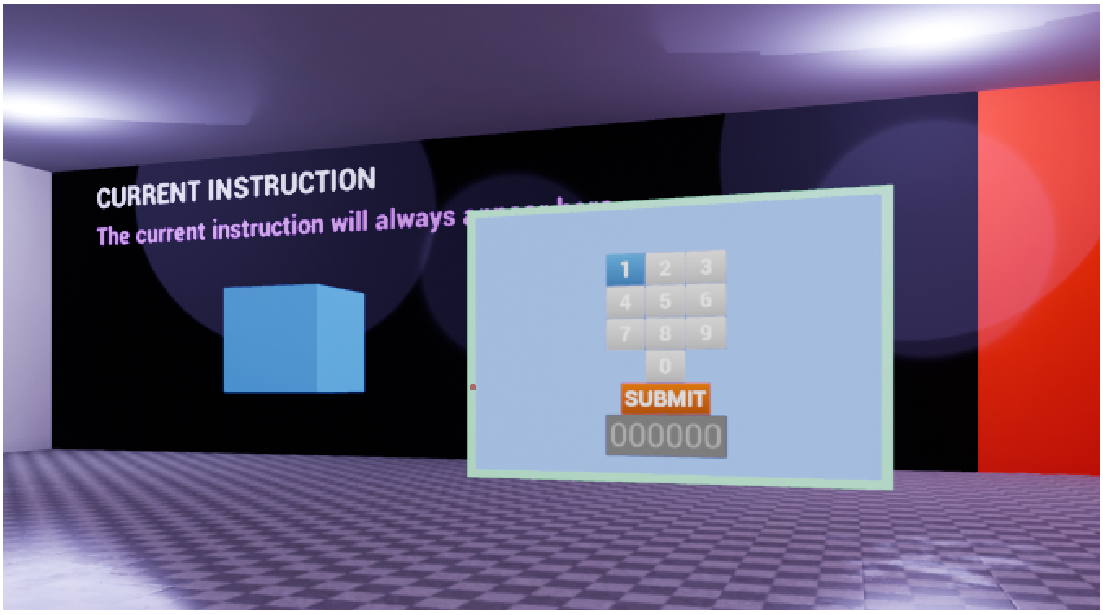


Figure 4.27: Player login keypad.

Teach Teleport Mechanics

The player is instructed on how to teleport (see Figure 4.28). Once the player teleports, the LIE "tutorial_teleport" is sent to the API and the player is instructed to practice teleporting before continuing to the next stage.

Teach Gaze Mechanic

The player is instructed on how to gaze at a gazeable object. When the player correctly gazes at a vertex, the dot turns red and a 'ding' sound is played to inform the player about the task completion. The LIE "tutorial_gaze" is sent to the API.

Teach Select Mechanic and Trigger LIE "LO 1(a)"

The player is instructed on how to select a vertex by first gazing at it and then pressing the trigger button. When the player selects a vertex, a 'ding' sound is

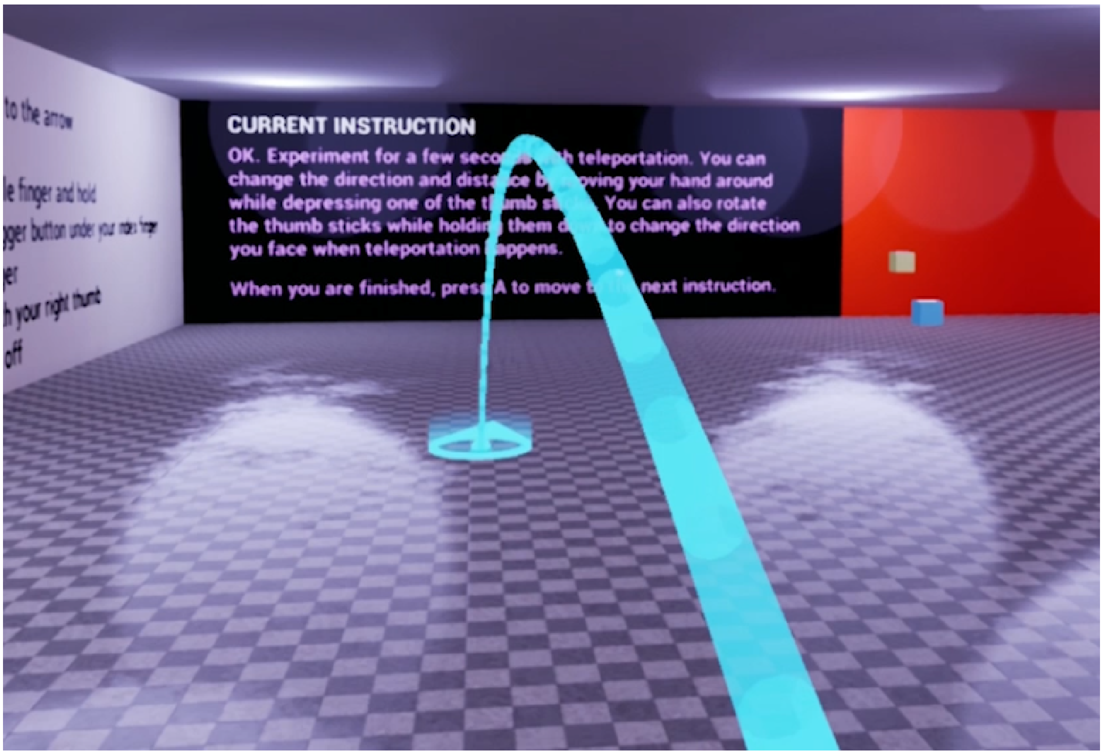


Figure 4.28: Player being instructed on teleportation.

played to indicate task completion. The LIE “tutorial_select” is sent to the API. The LIE “graph_vertices” is sent to the API to indicate that learning outcome 1(a) has been completed.

Teach Connect Mechanics and Trigger LIE “LO 1(b)”

The player is instructed on how to connect vertices by first selecting one, then gazing at another and pressing the A button to draw an edge between the vertices. Once the player has demonstrated a connection (see Figure 4.29), a ‘ding’ sound lets the player know the task is complete and the LIE “tutorial_connect” is sent to the API. The LIE “graph_edge” is sent to the API to indicate that learning outcome 1(b) has been completed. Because the player has created a first graph, the achievement “Graph Apprentice Level 1” is awarded (see Figure 4.30) and the LIE “graph_level_1” is sent to the API.

Teach Grab Mechanic

The player is instructed on how to grab a vertex and wave it around (see Figure 4.31). When the player has overlapped a vertex with a virtual hand and pressed the grip button, a ‘ding’ sound will let the player know the task has been completed and the LIE “tutorial_grab” will be sent to the API.

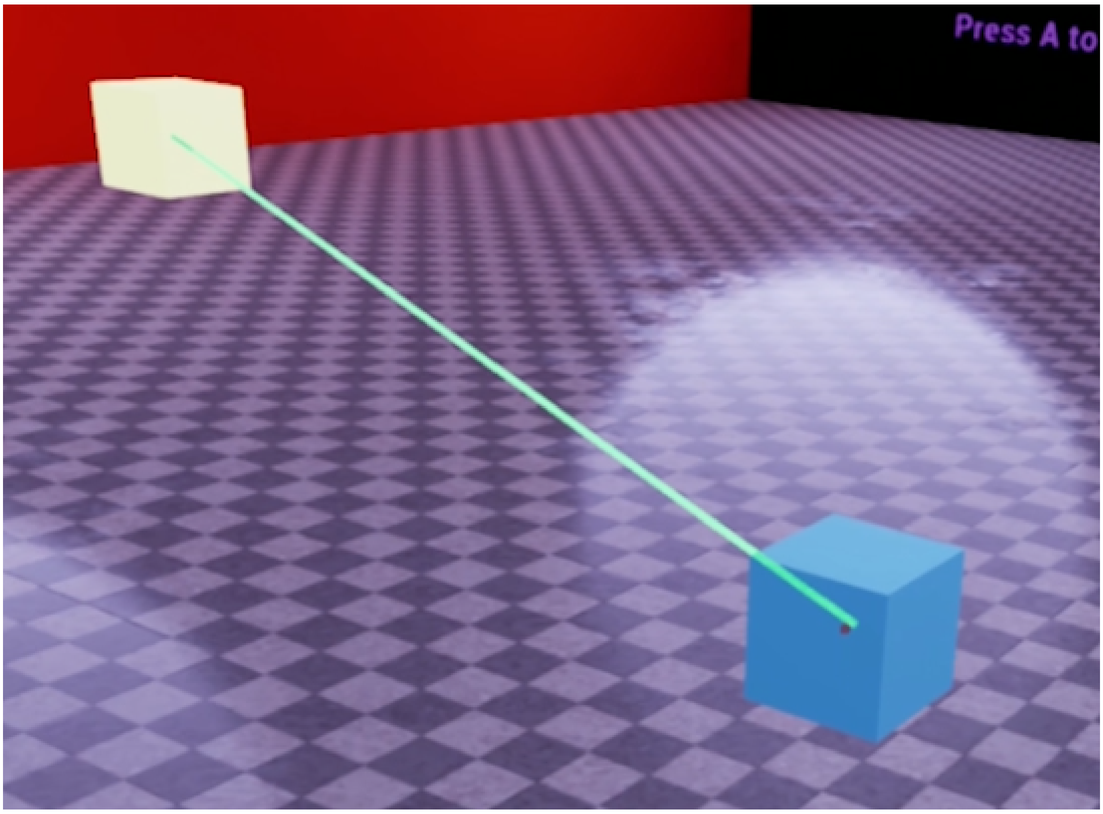


Figure 4.29: Player connects two vertices with an edge.

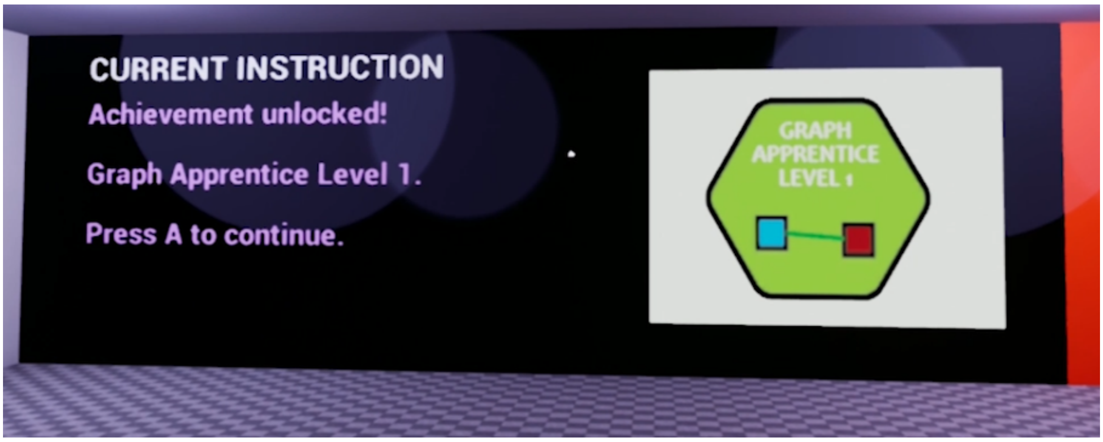


Figure 4.30: Player is awarded an achievement badge.

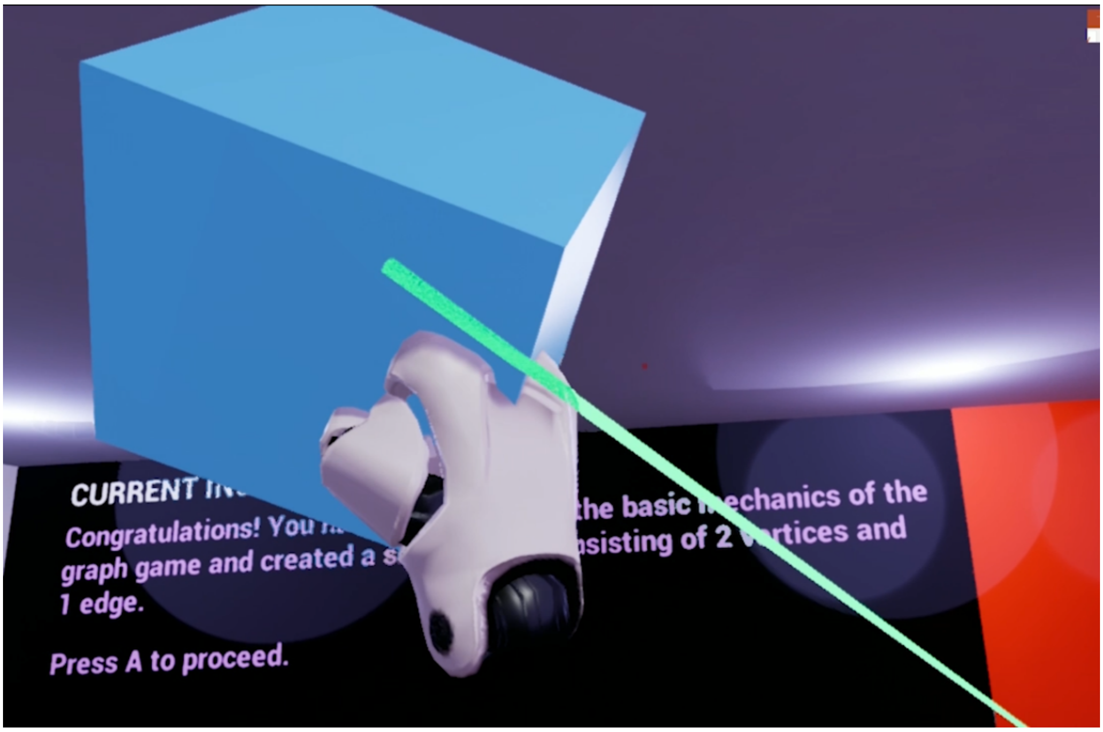


Figure 4.31: Player grabs a vertex and lifts it with a virtual hand.

Challenge 1

The player is presented with the following instruction:

> The final task in this tutorial is to complete 2 small graphs according to the rule on the wall to the right. The graphs are only complete when all 4 correct connections are made with no incorrect connections. The current correct and incorrect counts are displayed under the rule text. Complete the graph now.

The rule text on the wall to the right is as follows:

> Complete the graph (G) such that a vertex (Wi) is connected to a vertex (Wj) if and only if Wi and Wj are the same colour.
>
> In other words, connect only cubes of the same colour. Note: incorrect connections / edges are coloured red; remove those connections.

While the rule text has some *graph speak* that only some learners might be able to interpret, a plain English version of the rule is presented to ensure there is an accessible version of the rule text.

Figure 4.32 shows Challenge 1 in progress. The player receives immediate feedback with a message, such as “3 out of 4 edges correct with 0 invalid edges”. Any incorrect edges are coloured red, with correct edges coloured green, giving additional immediate feedback. As each connection is made the LIE “level1_exercise” is sent to the API with a value indicating the number of correct and incorrect connections. For example, the value sent might be “2:1” to indicate two correct and one incorrect connections. This allows exercise progress to be charted in the LAD. Once there are four correct edges and no incorrect edges, the challenge is complete. At this point the LIEs “graph_level_2” (for the award of an achievement badge) and “tutorial_end” are sent to the API. Because the player has now demonstrated the ability to complete a graph according to a simple rule, the LIE “graph_complete” is sent to the API to indicate that learning outcome 2(a) has been completed.

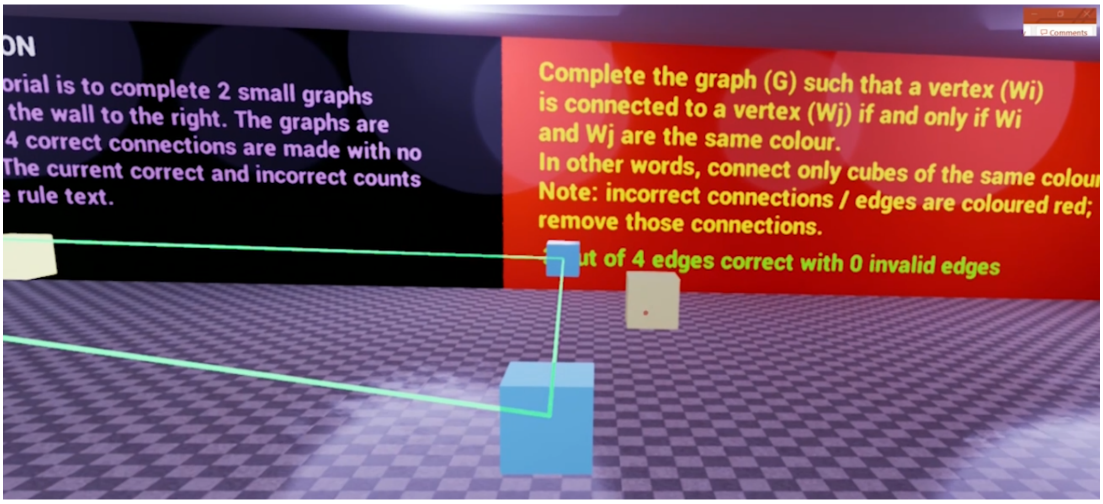


Figure 4.32: Challenge 1.

Social Graph Example

The player now progresses to level two, which begins with a real world application of graph theory. A social graph is rendered in a virtual room (see 4.33). A series of instructions draws the player’s attention to various aspects of the graph, highlighting certain vertices where appropriate (by making them flash). The instructions culminate with an explanation of how graphs can be used as the basis of recommendation engines, such as the ones used on Amazon and Twitter. With the lesson complete, the player is invited to *play about* with the graph, for example teleporting around and grabbing vertices to rearrange the graph. The number of teleports and grabs are counted. When the player is happy to continue, the player teleports onto a large red tile on the floor to go to the next section. At this point the LIEs "real_world_example_1_teleports" and "real_world_example_1_pickups" are sent to the API with values containing the number of teleports and grabs, respectively. This is used later to visualize engagement. At this point the LIE "real_world_example_1", which is used to determine length of engagement with the example, is sent to the API to indicate that the social graph example is finished with.

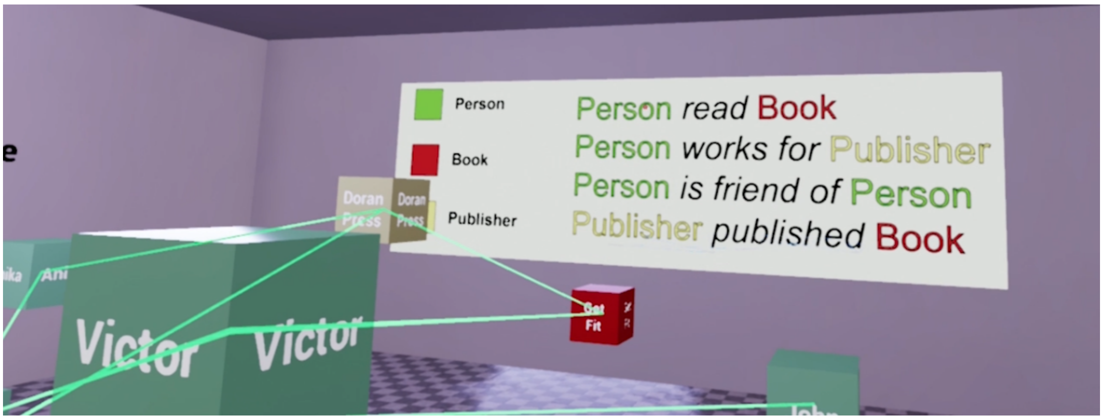


Figure 4.33: The social graph example.

The NLP Graph Example

The player is moved to a new virtual room where the concept of natural language processing (NLP) is touched upon through an example graph (see Figure 4.34). Similar to the social graph example, the purpose is to anchor the new experience in prior knowledge—particularly true of the social graph example, whereas the NLP example requires thinking about graph theory in what is likely to be a new context (artificial intelligence). Again, teleports and grab counts are sent to the API for engagement tracking purposes and when the player is finished playing around with the example, the LIE "real_world_example_2", which is used to determine length of engagement with the example, is sent to the API. The LIE "graph_examples" is sent to the API to indicate that learning outcome 3(a) has been completed.

Challenge 2

The player is moved to a new virtual room featuring a semi-complete graph. The player is presented with the following instructions:

> Now you can see a partially complete graph with some of the edges complete, but also incorrect ones coloured red. It differs slightly

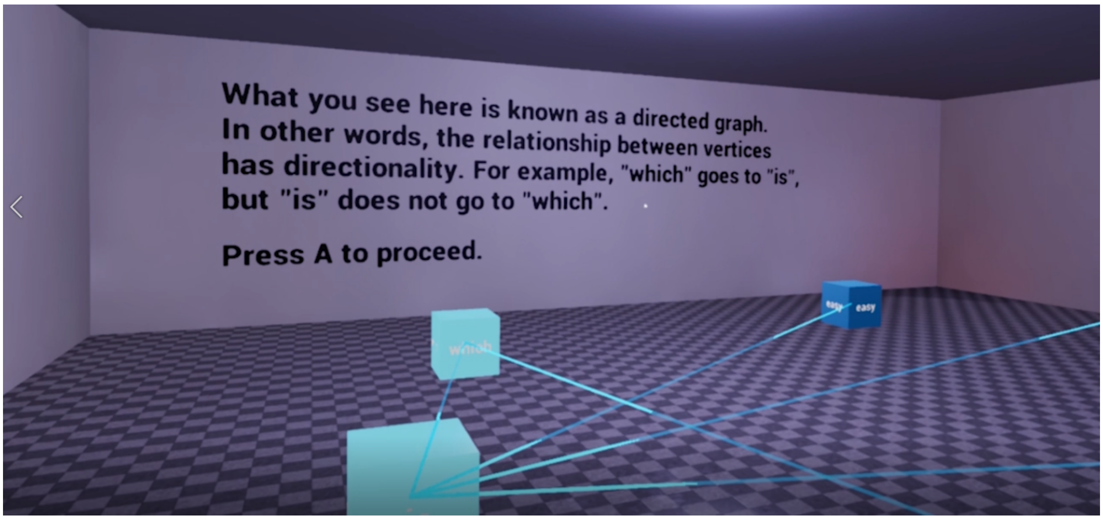


Figure 4.34: The NLP example.

> from a typical taxonomy or tree structure in that some of the vertices have multiple parents. Press A to continue.
>
> On the wall to the right you will see the rules for the graph. Study them for a moment and when ready complete the graph.

The rule text reads:

> Complete the graph such that two vertices Vi and Vj are connected by an edge if Vi is a type of Vj.
>
> Hint: A Jumbo Jet is a type of Airplane, A 747 is a type of Jumbo Jet, A 747 is also a type of Airplane.

The player is also given the current state of affairs: there are seven of fourteen correct connections already made, but two incorrect ones also (see Figure 4.35). This scaffolds the exercise slightly, showing the player examples of correct and incorrect connections (see Figure 4.36).

As the player completes the exercise, the scoreboard is updated to provide feedback and as each connection is made two LIEs are sent to the API: "toggle_connect:Level2" with a value indicating what connection was toggled on or off, e.g. "Rodent:Mouse"; "level2_exercise" with a value that equals the current correct versus incorrect count, e.g. "8:1". Once the challenge is completed, the "graph_level_3" achievement LIE is sent to the API.

Challenge 3

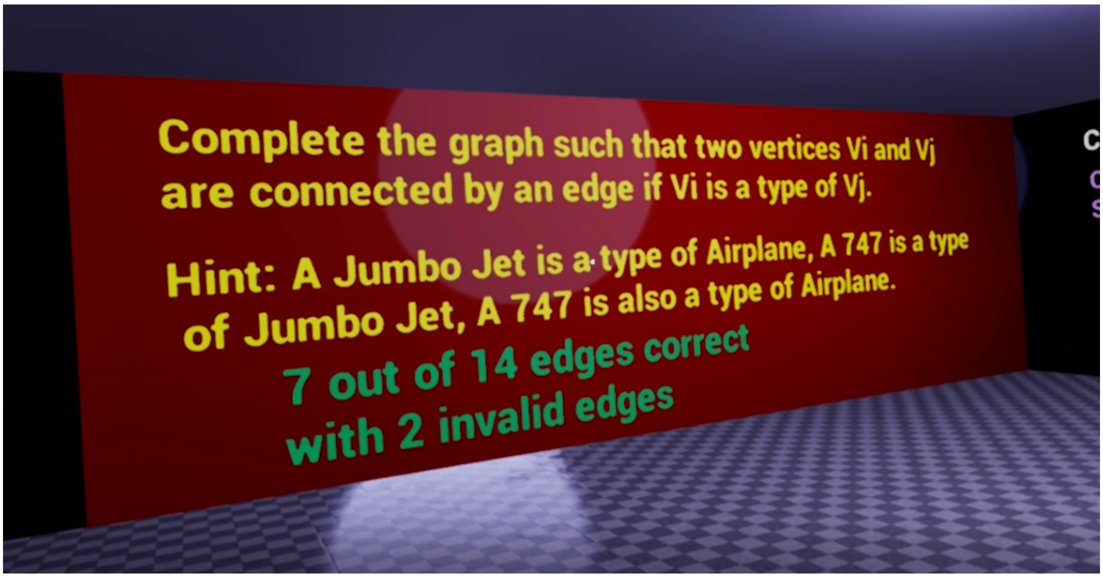


Figure 4.35: State of affairs prior to beginning challenge 2.

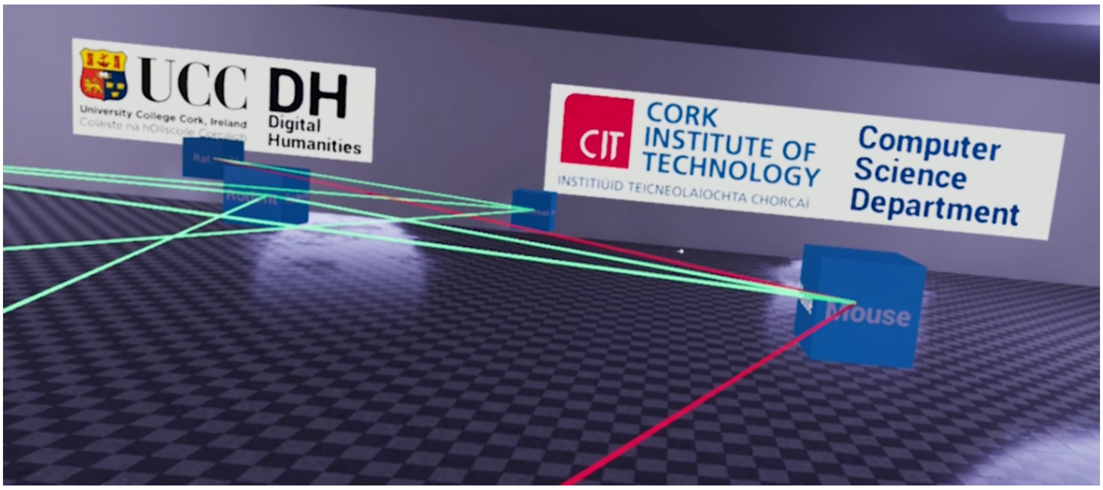


Figure 4.36: Examples of correct and incorrect connections.

Level 3 begins with a challenge against the clock. The player is presented with the following instruction:

> This level is a race against the clock. Your time will be recorded and added to a leaderboard. If you beat 90 seconds you will get the Speed King achievement. Study the rules for the graph. There is a hint on one of the walls if you need it. Teleport closer if you need to read it. Press A only when ready to start the challenge!

The rule text reads:

> Complete the graph such that two vertices (words) Wi and Wj are

> connected by an edge if the relationship between Wi and Wj is either:
>
> (1) Wi and Wj are synonyms (very similar in meaning)
>
> (2) Wi and Wj can be added together to form a commonly-used word or phrase

The hint on the wall (see Figure 4.37) offers players additional assistance if they have difficulty interpreting the rule text.

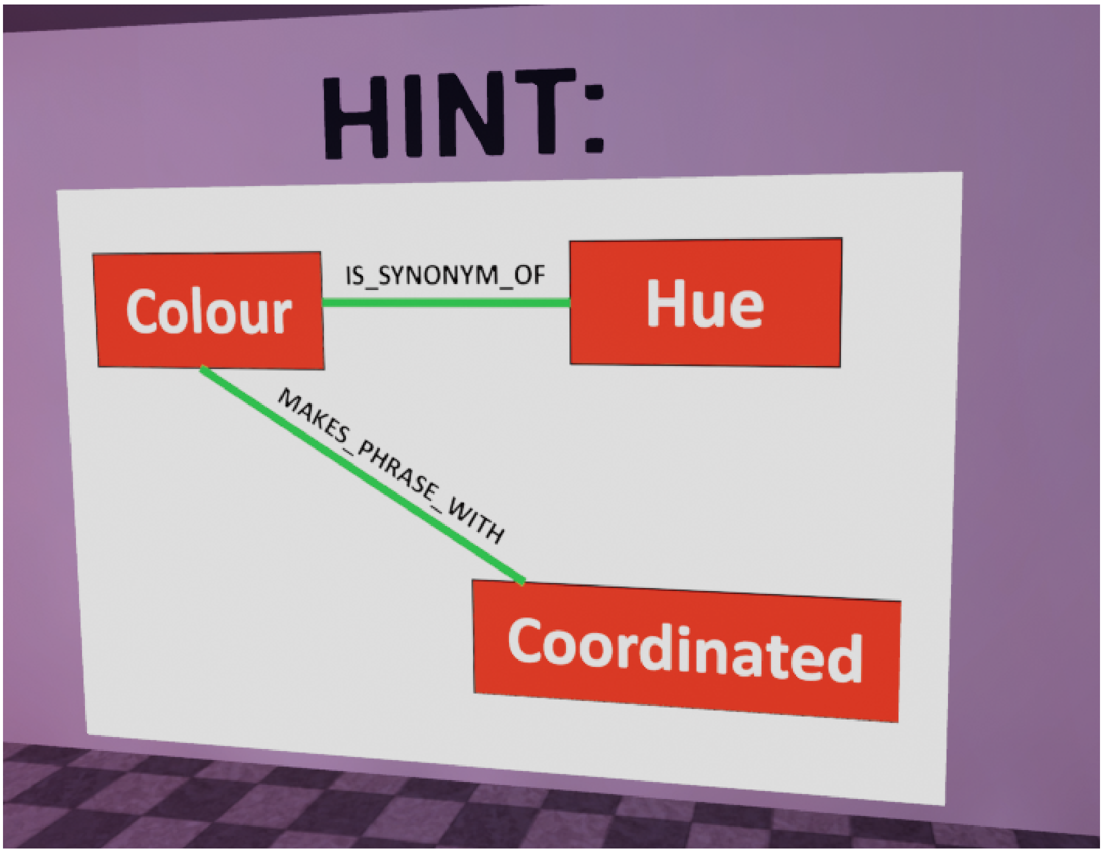


Figure 4.37: The challenge 3 hint.

The challenge begins with no connections made and the player must complete all nine with no incorrect connections to complete the challenge (see Figure 4.38). Just like the previous challenges, LIEs are sent to the API for an audit trail of correct versus incorrect, e.g. “5:2”, and connections toggled, e.g. “Shopping:Cart”. Once the challenge is completed, the elapsed time in seconds is sent as the value of an LIE with the key “speed_run_1”. LIEs for the *Graph Level 4* and *Challenging Times* (see Figure 4.39) achievement badges are sent to the API. If the time elapsed was under ninety seconds, the player is awarded the *Speed King* achievement badge and an LIE is sent to the API. Finally, an LIE is sent to the API for the final learning outcome embedded in the game, 2(b).

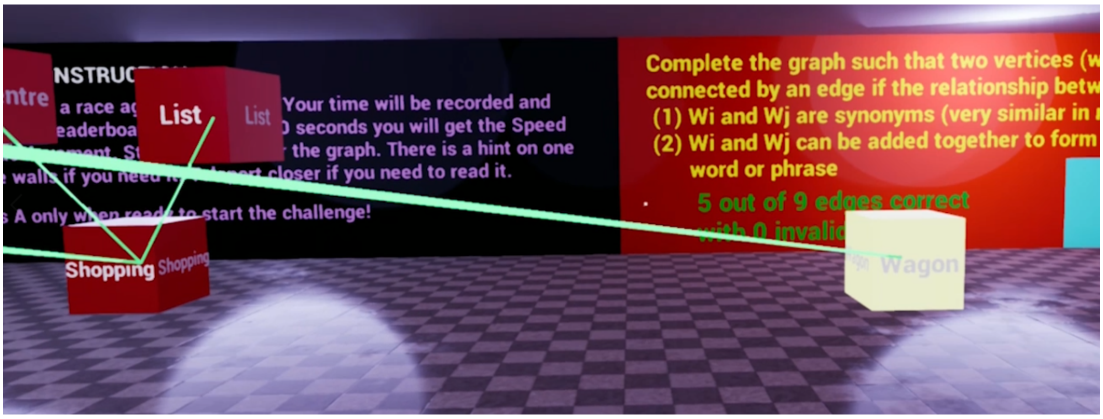


Figure 4.38: Player in the process of completing challenge 3.

Figure 4.39: Player is awarded the Challenging Times achievement, but fails to beat 90 seconds for the Speed King achievement.

Search Engine Example

Before the game is complete, the player is presented with the following message:

> Massive databases containing graphs just like this power search engines like Google, to suggest similar words or phrases to search for. As you can see from the solution, the suggestion of "shopping centre" is only one hop away from "shopping".
>
> That concludes The Graph Game. You can take off your headset now.

The object in Figure 4.40 is rendered as an example that anchors what they have learned in prior experience (searching the web). The Google screengrab includes two of the connections made during the challenge: *shopping centre* and *shopping list*. Once the player has examined it, the game ends and the player removes the HMD.

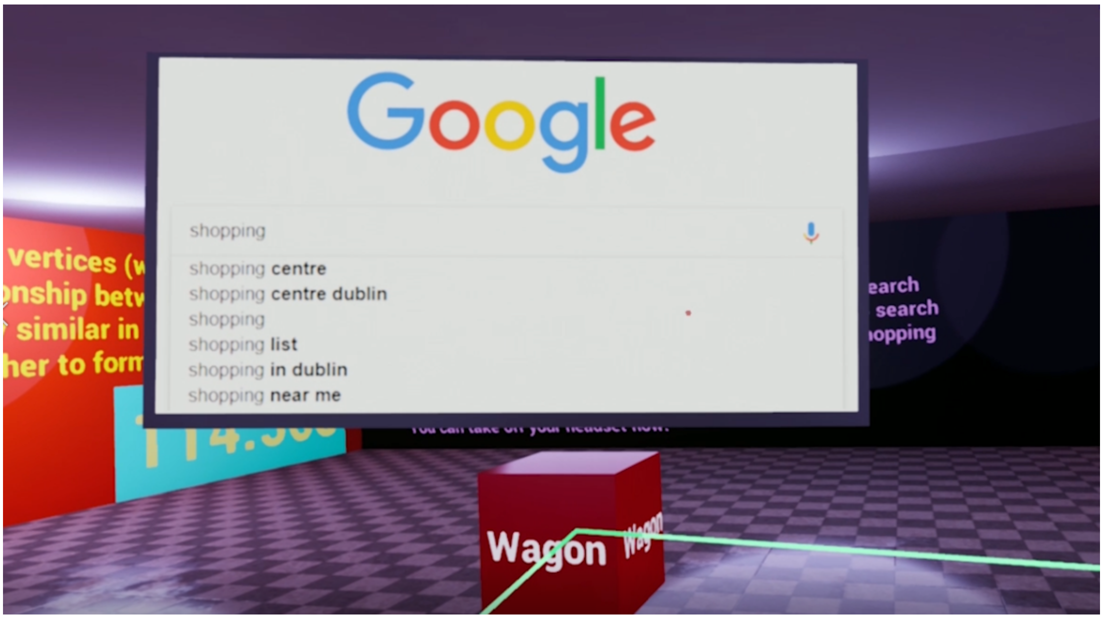


Figure 4.40: A final word about the relevance of what was learned.

4.5 Evaluation of the Game and Platform using the UDL Framework

While the AMDGBL advocates performing a formative evaluation, the evaluation performed here is closer to a summative evaluation, taking into account, as it does, the version of the game and platform at the end of the third iteration. In essence, it identifies where the game succeeds from a UDL perspective, but also identifies where it falls short. This future work is noted in Section 6.4.

The following list discusses the game and platform through the lens of the nine UDL guidelines detailed in Section 2.7.2. Many of the thirty-one checkpoints are referenced, with the number in brackets. Issues are highlighted in italics.

Recruiting Interest Involvement of learners in the game design contributes to autonomy, *but they could have been included earlier to have a greater say*

(7.1). Authentic activities and novel problems with an opportunity for experimentation were presented (e.g. social graph, search engine examples), *but there is no mechanism for a personal response* (7.2).

Sustaining Effort & Persistence The dashboard, particularly the visualization of learning progression, allows learners to see learning objectives, *though it could be presented in a more time-based way*; challenge 2 is scaffolded to show what should and should not be done; the performance visualizations could allow for discussion with learners about "what constitutes excellence" (8.1). Challenge is varied throughout, *though there is little freedom in allowing for varying performance* (8.2). *The game does not allow cooperation* (8.3). Feedback is timely (e.g. audio cues when tasks are complete and red versus green connections) and patterns of incorrect answers can be identified and discussed using performance visualizations in the dashboard (8.4).

Self Regulation While the dashboard supports self-reflection, through visualizations of learning progress (9.3), *the game itself needs to be integrated in a self-reflective framework* (9.1). *The game lacks a means of managing frustration, for example when players struggle with challenges—there is no way of leaving a challenge early, for example* (9.2).

Perception While the game does not allow customization of font or image size, the locomotion mechanic means players can get close to text and other images; with the grab mechanic, layout of graphs can be manipulated to suit preference; *however, the game lacks flexibility in terms of colour contrast* (1.1). *The game and platform lack a text to speech function, limiting accessibility for the visually impaired*; however, the use of audio cues, such as the 'ding' sound when tutorial tasks are complete will assist some players; the haptic feedback of the controllers will assist when players have depth perception issues while grabbing vertices (1.3).

Language & Symbols The game features terminology specific to graph theory, however plain English explanations have been given (vertex is an object, edge is a connection, and so on); the rules text had plain English alternatives or hints (2.1, 2.2). All instructions are only available in English, and while text can be internationalized, *this has not been done*; *the final challenge, in particular, requires a knowledge of English phrases or synonyms, which would not translate well to other languages* (2.4). There is a good mix of alternative media—graph concepts are explained in text form along with images (such as the graph legend in the social graph example and the hint for challenge 3) and the graphs themselves are an additional representation in 3D format; the links between each are clear (2.5).

Comprehension New knowledge is anchored in prior knowledge—it is anticipated that students will be familiar with social graphs and search engines, as well as taxonomies of species, and even the NLP graph features a familiar sentence; some of these make "cross-curricular connections", for example the NLP graph for students of artificial intelligence (3.1). Cues and prompts are used to draw attention to key features, for example the flashing vertices in the real world examples (3.2). Scaffolding supports graduated learning; information is "chunked" to make it more digestible (3.3). New ideas are embedded in familiar contexts; *however, the game could be improved in terms of generalizing learning to new situations* (3.4).

Physical Action A range of motor action is supported and the learner can move at a speed that suits; *however, alternatives to physical interaction could be provided, such as voice commands* (4.1). *The game may not be accessible to all, for example those who suffer severely from VIMS; therefore alternative access means should be supported, for example a non-VR 3D version of the game* (4.2).

Expression & Communication *The graph game is but one tool in a wider curriculum and so other media should be included, such as social media, storytelling (e.g. comics), and so on, and learners should be supported in their practice with fluencies such as visual, audio, reading, and so on* (5.1, 5.2, 5.3).

Executive Functions The dashboard supports goal setting, *but it could be improved to provide estimates of remaining effort, for example* (6.1). The hierarchical nature of the learning progress visualization allows longer-term goals to be decomposed into "reachable short-term objectives", *but additional prompts could be added to ask the learner to "stop and think"* (6.2). *The game and dashboard do not support note-taking, but this could be added—for example, the graph game could allow voice recording for notes to be taken* (6.3). Progress can be monitored in the dashboard, *but there could be additional support for feedback and an explanation of performance against rubrics, for example*

(6.4).

The UDL framework is comprehensive and it is difficult to imagine that any single resource could satisfy all thirty-one checkpoints flawlessly. The evaluation above suggests that the game and the platform is successful from a UDL perspective, but that there is still work to do to improve the game in terms of accessibility, providing actionable information, allowing players cope with frustration, and other issues.

4.6 Chapter Conclusion

This chapter provided a comprehensive detailing of how the AMDGBL platform (incorporating API and web-based dashboard) and the VR-based graph game were developed. It followed the steps in the AMDGBL. The platform API was implemented using Spring Boot / Java and receives JSON requests for learner interaction events, which are then stored in a MySQL database. It can serve out a range of responses, such as badges, leaderboards, learning outcomes and exercise data. The web-based dashboard was developed using Spring MVC with Thymeleaf and Bootstrap for the web pages. The graph game was developed using Unreal Engine 4 due to its popularity and support for VR. The phases of the AMDGBL were followed: the analysis and design featured a needs analysis, development of learning outcomes mapped to Biggs's SOLO taxonomy, mapping of learning mechanics to game mechanics, mapping of game mechanics to game dynamics and aesthetics, and the addition of gamification features. The game and platform designs were formatively evaluated for flow, balance, motivation, and mapping of learning to the game. The build phase detailed the choice of game engine, the implementation of game mechanics and the implementation of the game structure, which went sequentially through the elements of the game. Finally, the game and platform were evaluated as a whole using the UDL framework, which found the game was well-designed in many respects from a universality point of view, but highlighted several areas for improvement.

Chapter 5

Studies Undertaken

5.1 Introduction

Two studies were undertaken to evaluate the AMDGBL. The first was a study involving learners and the second a study involving practitioners.

The purpose of the learner study was to evaluate a game developed using the model to see if it was successful from a number of standpoints, such as effectiveness, motivation, and universality of design. It was not the intention of the learner study to be definitive about the success of the model, but to give a solid indication that it was worthy of presentation as part of a case study to DGBL practitioners in a second study (see Section 5.4.2 for more on how the case study was constructed and presented). The purpose of the practitioner study was to gauge whether the approach of the model was seen to be of benefit to practitioners and organizations engaged in the development of DGBL solutions. By completing the learner study prior to the practitioner study, it was possible to employ learning analytics techniques to create visualisations that could be used as discussion points with the practitioners in the second study.

The following sections in this chapter describe the research paradigm adopted, and give a detailed overview of the two studies, presenting the methodologies used in each, the results generated by each, and discusses the results obtained.

Two texts are cited frequently in this chapter (alongside other citations): *Social Research Methods* by Bryman (2008) and *Research Methods in Education* by Cohen et al. (2017). Each is comprehensive, providing detail on qualitative, quantitative and mixed methods approaches to research. Editions of these books have been frequently recommended as texts for research methods modules in universities around the world. A quick internet search shows editions of Bryman (2008) being recommended for courses in Trinity College Dublin, University of Leeds, De Montfort University and many more. Similarly, editions of Cohen et al. (2017) are recommended for courses in University of Plymouth, University of Central Lancashire, Middlesex University and many more.

5.2 Research Paradigm

A research paradigm has variously been called a *world view*, *epistemological stance*, a set of *shared beliefs among researchers*, or *model examples of research* (Morgan 2007). The idea of paradigm shifts was popularised by Thomas Kuhn (1962). It is a scientific revolution where a dominant paradigm is supplanted by a new one that is capable of studying new or emerging phenomena that the previous paradigm cannot.

Morgan (2007) writes that the notion of a research paradigm as an epistemological stance is the most commonly used meaning in social scientific research, to which the studies here are largely aligned. However, many of the most respected writers on research paradigms tend to use the term *world view*. This researcher elects to choose the term epistemological stance (although this researcher also likes to use the more informal phrase *philosophical position*) and to address the often asked ontological, epistemological and methodological questions, as suggested by Guba (1990):

- Ontological: What is the nature of reality?
- Epistemological: What is the relationship between the inquirer and the knowable?
- Methodological: How does the inquirer go about knowing the knowable?

It should be noted that while these are the three most commonly written about components of the quest for knowledge, others include axiology (the role of values in that quest) and rhetorical structure (how the research is written and presented) (see Ponterotto 2005).

Arguably, the three most common stances are categorised as positivism (primarily associated with quantitative methods), constructivism (primarily associated with qualitative methods), and pragmatism (often associated with mixed methods). Other less common ones abound, such as critical-ideological (challenging the status quo) (Ponterotto 2005).

Feilzer (2010) makes a good argument for the addition of pragmatism to the other two dominant paradigms listed, summarising the position of proponents of pragmatism as one that doesn't accept the dichotomy of positivism and constructivism, and that the two have many commonalities; indeed, the separation may largely be a political one among warring communities of scientists. To put pragmatism in simple (perhaps crude) terms, it is about selecting what works.

Returning to the questions about ontology and epistemology, taking a pragmatist stance makes simple answers difficult. It is not possible to simply say that the nature of reality (ontology) is a single, verifiable truth, nor is it possible to only say that it is socially constructed. The relationship between inquirer and the knowable becomes similarly complicated. This leads to the abandoning of this older "philosophy of knowledge approach" in favour of a paradigm (i.e. pragmatism) that goes beyond mere "practicality" (or "what works") (Morgan 2014).

Morgan (2014) offers Dewey's model of inquiry (see Figure 5.1) as a basis for pragmatism. It is an iterative model with reflection at its heart—this reflection on beliefs leads to pragmatic choices about actions, which in turn may lead to a new choice of beliefs, which lead to new pragmatic choices, and on the cycle goes. As Morgan writes:

> Based on the work of John Dewey [and his model of inquiry], pragmatism points to the importance of joining beliefs and actions in a process of inquiry that underlies any search for knowledge, including the specialized activity that we refer to as research.

In concluding this section, this author states that the pragmatism paradigm (and by extension a mixed methods research approach) is adopted, particularly with the learner study. Because the learner study becomes a case study for the practitioner study, it can be said that pragmatism prevails throughout all of the research carried out for this thesis.

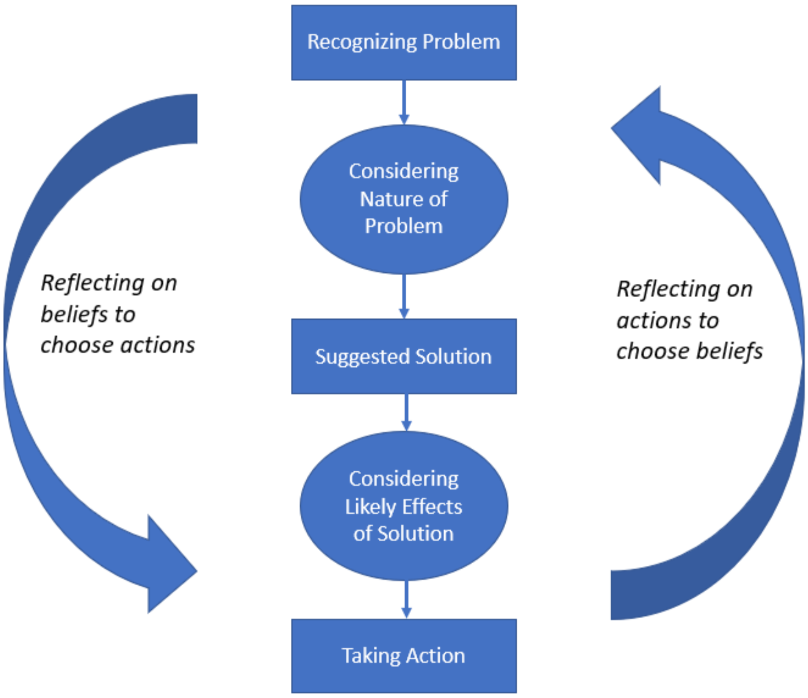


Figure 5.1: Dewey's Model of Inquiry, reproduced from Morgan (2014).

5.3 The Learner Study

5.3.1 Methodology

5.3.1.1 Overview

Because the first study involved learners playing the graph game, a methodology needed to be devised that would capture several types of data for analysis (this is the recommended approach of the AMDGBL and is similar to playtesting in the video games industry). This included observations about the way the learners played the game, any thoughts they verbalised as they played, gameplay data captured by the game engine, and post-play feedback from the learners about their perceptions of a number of variables (such as how effective the game was, how efficient it was, how motivating it was, and how universally it had been designed).

This meant that both qualitative (observations, think aloud) and quantitative (questionnaire responses, gameplay data) would be required—the second study involving subject matter experts goes further, using open-ended questions in a survey (qualitative). According to Cohen et al. (2017), we tend to "use all the means and data at our disposal to understand a situation". The mixed methods approach to research has increased greatly in popularity in recent years to the extent that it is viewed as a third methodological movement / research paradigm / path—Cohen et al. cites a number of authors using one of the three phrases to describe the addition to quantitative and qualitative of mixed methods as a third way.

Creswell et al. (2011) offers the following definition of mixed methods as a research methodology or approach (numbering added to aid later discussion):

> 1. focusing on research questions that call for real-life contextual understandings, multi-level perspectives, and cultural influences;
> 2. employing rigorous quantitative research assessing magnitude and frequency of constructs and rigorous qualitative research exploring the meaning and understanding of constructs;
> 3. utilizing multiple methods (e.g., intervention trials and in-depth interviews);
> 4. intentionally integrating or combining these methods to draw on the strengths of each; and
> 5. framing the investigation within philosophical and theoretical positions.

The approach taken by this thesis can be examined using that definition (the numbering matches that used in the definition above):

1. The research questions look at the model (and game and platform implemented) from the perspectives of learners and subject matter experts (instructional designers and developers of DGBL solutions); the studies attempt to gain an understanding of how the model has operated using a real-life context (teaching a real subject to real students) and also in comparison to how subject matter experts carry out their duties.
2. Quantitative methods are employed rigourously (e.g. applying learning analytics to captured gameplay data, which is a way of reconstructing the events as they were) and qualitative methods are employed (e.g. trying to understand the way learners engage with the game, such as differing strategies employed in solving challenges; having subject matter experts fill in open-ended questions to understand their conception of how DGBL should be employed).

3. Multiple methods are employed: applying learning analytics to gameplay data (quantitative), observations (qualitative), think aloud (qualitative), closed questionnaire questions (quantitative), open-ended survey questions (qualitative).

4. The combination of the methods is not accidental—for example, observations can be used to corroborate what the analysis of gameplay data says and vice versa (a specific example is the trial and error discussion in Section 5.3.4).

5. The philosophical approach of the author of this thesis aligns with the mixed method approach, that is that research should ideally be multi-disciplinary and pragmatic, both interpretative and empirical—follow what works, even if that puts the researcher outside of their comfort zone. Creswell et al. (2011, citing Green 2007 on tensions) writes that "mixed methods research ... represents an opportunity to transform these tensions [created by different philosophical positions] into new knowledge through a dialectical discovery." In other words, by taking a mixed methods approach, knowledge could emerge that would not otherwise have been discovered.

Point 4 above is an example of triangulation, which is where more than one method is used, resulting in a higher level of confidence in findings (Bryman 2008, p.379). Triangulation, along with a reduction in bias and the compensation of strengths and weakness across research strategies, increases the accuracy and reliability of data (Denscombe 2014). To avoid confusion with other meanings of the word 'triangulation', Creswell and Clark (2011) offer the alternative term *convergent parallel design*. Figure 5.2 shows a simplified version of their flowchart (p.79). The full version of the flowchart ends with the instruction:

> Discuss to what extent and in what ways results from the two types of data converge, diverge, relate to each other, and/or produce a more complete understanding.

However, their flowchart might imply that convergent parallel design is limited to two separate studies, whereas as can be seen from Section 5.3.3.4.4, more than two in parallel is possible.

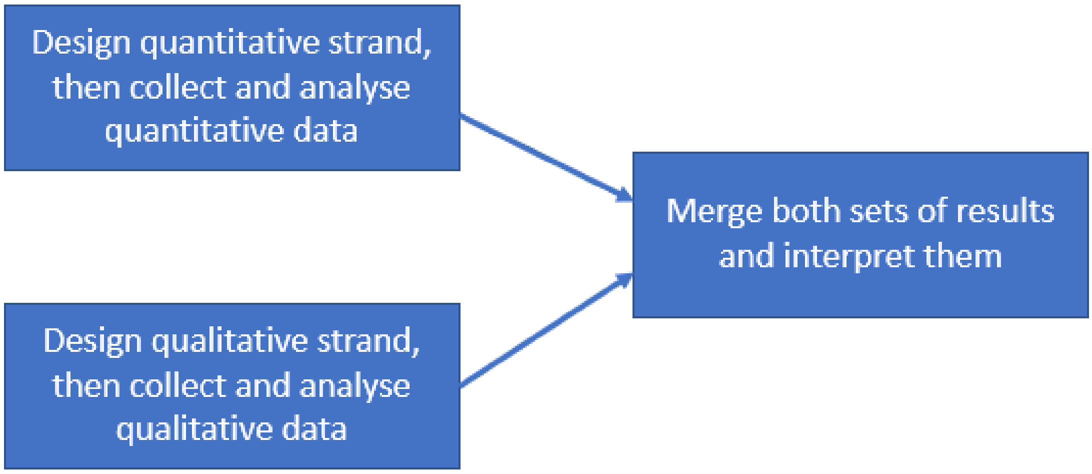


Figure 5.2: Convergent Parallel Design.

5.3.1.2 Study Design

There could be no study without a game and platform. The design, development and evaluation of these is discussed in Chapter 4.

A laboratory-based experiment appeared to be the most realistic approach as opposed to an ethnographic one. CIT does not have a laboratory equipped with enough VR-capable machines to replicate a typical lab-based tutorial where up to twenty students are present. The other alternative of self-paced instruction, where the student engages in the DGBL activity at home at a time of their choosing, would require a PC powerful enough to use an Oculus Rift. Either approach was therefore not an option. However, the immersive nature of VR should mean that there is little difference between a field-based experiment and a laboratory-based one. The participant cannot see anything but the virtual world they inhabit. There would be a difference in terms of distraction or interruptions from friends or family.

Two locations were used: a training room and a computing laboratory. Both had open areas of at least 3 metres by 3 metres, which allows for a great degree of freedom of movement.

Participation in the study began with the signing of a consent form to ensure the participant understood, for example, why they were taking part, what they would be doing and what would happen to their data. This is discussed in detail in Section 5.3.1.3.

5.3.1.3 Ethical Considerations

Diener and Crandall (1978) list four main areas of ethical principles in research:

1. Whether there is *harm to participants*;
2. Whether there is a *lack of informed consent*;
3. Whether there is an *invasion of privacy*;
4. Whether *deception* is involved.

As Bryman (2008) points out, there is some overlap in the main areas; for example, it is difficult to imagine consent being informed if deception was involved.

There are a number of competing views on research ethics, such as a *cost/benefits ratio* approach where the benefits of the research to society are weighed against personal costs to the participants, and the *absolutist* approach where a higher-order moral principle is immutable regardless of the research context, even where the benefits to society far outweigh the cost to the individual (Cohen et al. 2017, p.113-14).

There are other stances as outlined by Cohen et al. (2017) and Bryman (2008). This includes the view that ethical transgression is pervasive and, as it is in real life, so it is in research; others argue that more or less anything goes, in a relativist way, because whatever deceptions are perpetrated by researchers will be trivial compared to those perpetrated by large corporations (there are exceptions, with the Stanford Prison Experiment probably the most famous example, which is discussed by both Bryman and Cohen et al.). The *deontological* stance considers acts as being intrinsically good or bad and the *consequentialist* stance assesses the consequences of acts before making a judgement as to their ethical integrity.

Ultimately, the researcher, after taking into account ethical guidelines, legislation, feedback from ethics committees, and so on, needs to decide what is ethical. As Cohen et al. (2017) put it, “there are rarely easy, ‘black-and-white’ decisions on ethical matters” and ethics considerations touch all parts of the research process and researcher behaviour.

The ethical approach to this research was from a largely deontological approach, eschewing the notion that the end justifies the means or that it is relative. But it was not a completely black-and-white situation: for example, the game is designed to mitgate the risk of VR sickness, but cannot entirely eliminate the risk. Taking an absolutist perspective might have rendered any research using VR technologies as impossible. To take the cost/benefits ratio approach, the benefit to society greatly outweighed any potential of harm to the individual participant.

Harm can be defined in several ways: physical, psychological and reputational, for example. In the case of VR, as discussed in Section 2.4, there are a number of minor physical and psychological issues associated with the use of VR, though these were mitigated both through the design of the game and the design of the experiment. The use of a teleport mechanic for locomotion is discussed in Section 4.4.4.2. In addition, the game was designed to last about thirty minutes (as mentioned in the information sheet) to reduce the after effects of VR immersion (Section 5.3.3.2.1 shows that typical gameplay sessions were in the region of 20 to 40 minutes, with a median time of 30 minutes and 16 seconds).

Almost always, getting informed consent from all participants in a study is considered ethically necessary. There are some exceptions where informed consent would either be dangerous for the participant or render the study impossible. Both Bryman (2008) and Cohen et al. (2017) discuss the somewhat controversial research of Laud Humphreys conducted in the late sixties and early seventies on the homosexual ‘tearoom trade’ and the lookout ‘watch queen’; the watch queens carry out their activity in public and so covert observation is possible, but also might be preferred where the participant would not willingly take part due to a fear for their safety (a *cost/benefit ratio* approach could be used in such a scenario to decide if there is a greater good to be served by the research). Humphreys did protect the identifies of the unwitting participants in his publications.

It is difficult, perhaps impossible, to present all possible information about a study to potential participants (Bryman 2008). There can be minor transgressions, such as underestimating the amount of time the participation will take—this can be to avoid dissuading participants from signing up—and withholding some information in the hope of not contaminating the data gathered. In this study, the amount of participant time was initially underestimated at about 30 minutes and this was corrected for iterations 2 and 3 by informing participants that participation was likely to take at least 45 minutes. By the end of the study, it was apparent that this was also an underestimate and that 60 minutes would have been more appropriate. That minor transgression can be put down to inexperience of conducting this type of research rather than a deliberate attempt to make participation less onerous.

For this research study, the methods were outlined in some detail on an information sheet (see Appendix A.3), which was published on a website and also presented to participants before they participated in the study (as a final verification that they were informed about the study). Some of the key points on the information sheet are:

- The research area: Game Based Learning, Learning Analytics, Visualisation of Learning, Virtual Reality;
- How long participation is likely to take;
- That a game will be played using VR technology (Oculus Rift and touch controllers);
- That the game teaches some fundamentals of graph theory;
- Some examples of the application of graph theory, in the hope that participants see the relevance of graph theory to their lives or work;
- A participant profile: anyone over the age of 18 with no prior knowledge of VR, graph theory, and so on;
- Some background on learning analytics and the mapping of learning in the graph game;
- Ethical and privacy issues were addressed:
  - How the gameplay data will be used;
  - What will happen to the data (including confidentiality);
  - The hiding of identity.
- Some notes on whether there are disadvantages in taking part: specifically, that some users of VR experience mild symptoms of VR motion sickness but that the game has been designed to mitigate this effect;
- A note that UCC's Social Research and Ethics Committee approved the study;

- Contact information for the researcher and supervisor.

In addition to the main text, the website version of the information sheet had an embedded video showing some early prototyping, and featuring the primary game mechanic of connecting vertices with edges. Hyperlinks were included, such as an example of a social graph, images of the Oculus HMD and touch controllers, and a link to the UCC Social Research Ethics Committee web page. Perhaps the greatest ethical concern was the use of VR and the potential for VR motion sickness. A hyperlink[1] to a comprehensive article on VR Motion Sickness and how to avoid it was included. This was an attempt to ensure that participants would be as fully informed as possible about the potential risks of taking part.

A consent form (see Appendix A.4) was more explicit about participation and the use of data. Participants were asked to sign the consent form to agree that:

- participation was voluntary;
- the nature and purpose of the study had been explained in writing;
- permission was being given that a questionnaire would be filled in and observational notes taken;
- the participant could withdraw from the study at any time without repercussions;
- permission could be withdrawn to use data gathered within two weeks (and that it would deleted in that case);
- anonymity will be ensured when writing up the research.

The research protocol (see Appendix A.5) includes some additional notes to be read to each participant before participation begins, including that the taking of notes includes verbalisations (think aloud protocol).

The combination of information sheet and consent form as described above, notwithstanding the discussions previously about the grey areas of ethics, should ensure that consent, when provided by the participants, was as informed as it could practicably be and no deception, harm or invasion of privacy befell any participant.

In the case of the learner study, a submission was made to UCC's Social

[1]https://vr.arvilab.com/blog/combating-vr-sickness-debunking-myths-and-learning-what-really-works

Research and Ethics Committee applying for ethical approval. The submission, a completed proforma form, outlined the type of research being undertaken, the questions it was trying to answer, who was participating and the methods that would be used to carry out the research. A combination of check-lists and a disclosure of any ethical queries on the part of the researcher sought to highlight any obvious ethical issues for the committee to consider. The committee was rigorous in its approach (there are critics of ethics committees who suggest they are too concerned with protecting institutions from legal action—van den Hoonaard (2001) questions whether there is a moral panic), asking several questions seeking clarification and offering advice, before approval was finally confirmed on 18th January, 2018 (see email in Appendix A.1).

There is a danger that having been successful in attaining ethical approval after such a rigorous process that the researcher assumes that all ethics issues have been addressed. As Bryman (2008, p.117) points out, ethical issues can arise at all stages. It is also not practical to inform an ethics committee about the minutiae of every study, and so as the study progressed, the question of ethics was never far from the author's mind.

5.3.1.4 Recruitment of Participants

A number of factors had to be taken into account when recruiting participants for the study. The first is that the sample chosen should ideally be representative of the target population, which is computer science students in both full-time undergraduate and part-time postgraduate courses. CIT's computer science department, while always having a strong number of full-time undergraduate students, has increasingly offered courses to postgraduate students on a part-time and often online basis. The most recently available CIT annual report (Cork Institute of Technology 2018) states that of the 14,591 students enrolled at CIT, 6,664 (45.7%) were part-time with 7,927 (54.3%) full-time. There are no publicly available figures specific to the computer science department.

The second consideration is that the sample size be large enough that *saturation* is reached in what is a study driven primarily by a qualitative approach. Saturation is a term used in grounded theory where emerging concepts have been explored to the extent that no new insights are being generated (Bryman 2008, p.416). To some extent this means that the required sample size is unknown prior to beginning the study.

Ultimately, the method of sampling used can be described as purposive. Purposive sampling is non-probabilistic and relies on the judgement of the researcher to determine if the participants chosen for a study are representative. Purposive sampling is a compromise: it provides greater depth, but less breadth than probability sampling (Teddlie and Yu 2007). It is not a random sample, so it cannot be described simply as a convenience sample. A number of criteria were used when selecting the sample, which means it also shares some characteristics with quota sampling (Bryman 2008, Cohen et al. 2017).

Because of the mix of full-time undergraduate and part-time postgraduate computer science courses, participants were recruited from the pool of existing full-time computer science students and a more mature and educated group that were suited to postgraduate computer science programs. Full-time students tend to be under the age of 25—CIT's annual report for 2015-16 states that 1,096 (13.8%) of the 7,927 full-time students were *mature*, which Ireland's Higher Education Authority (HEA) defines as being 23 years old on the 1st of January of the year of starting as an undergraduate with the higher education institution.

An email was distributed to students in CIT's computer science department—year coordinators were asked to forward the first email in Appendix A.2 to the students in the class they coordinate. The second email in Appendix A.2 was distributed to all staff in CIT. Staff members in CIT are highly educated (a significant proportion of staff are categorised in the annual report as academic, technician or researchers, all of which typically require at least a level-8 honours degree or higher). CIT staff members can be described as a potential sample of convenience, but one that is likely to yield a range of participants suited to postgraduate study in the computer science department—some postgraduate programmes require prior degrees in a cognate discipline (such as ICT, engineering or mathematics), whereas others, such as information design and development, do not.

33 responses were received expressing an interest in participating in the study. 20 were computer science students and 13 were members of staff. When follow up emails were sent to arrange a date and time of participation, 16 computer science students and 10 members of staff agreed a date and time. By

the time it came to participation in the study, 12 computer science students and 8 staff members showed up. The split of 12 full-time to 8 potential part-time students was close to the reported 54.3% to 45.7% ratio in the annual report. Unfortunately, female response rates (judging by respondent names) were particularly poor—3 agreed a date and time and only 2 showed up—and so it was not possible to reach what would have been a representative quota of 4, based on the percentage of female computer science students enrolled in Irish third-level institutions (discussed in Section 5.3.3.3.7).

The majority of participants were not well known to the author, however three of the student participants had previously attended lecturers given by the author. These were students who had a particular interest in the technology. Because the students were not currently attending lectures by the author and could expect no favour (such as an improved grade as a reward for participation), there appeared to be no ethical concern. In addition, two of the non-student participants were colleagues of the author, and these were allowed to participate, again because of their interest in the technology.

5.3.1.5 Observations

One of the advantages of observations is that it allows behaviour to be observed directly, leading to more authentic results than would be obtained from mediated or inferential approaches (Bryman 2008, Cohen et al. 2017). There can also be a difference between what people say and do and observation provides a more accurate slice of reality. It allows an opportunity to gather rich contextual information that is verbal, non-verbal and physical (Clark et al. 2009).

The purpose of the observational method was two-fold. The first was to gather clearly categorised variables based on:

- Issues encountered by players from a UDL perspective
- Strategies employed to complete challenges
- Pedagogical observations

The second was to discover any phenomena and to consider their significance later, developing a narrative account of participant behaviour (as described by Bryman 2008, p.257).

Types of observation can be placed on a continuum from unstructured to highly-structured (Cohen et al. 2017), with semi-structured being somewhere around the middle of that continuum. The former (unstructured) allows observation to be more responsive to unforeseen events, whereas the latter (highly-structured) will have pre-ordained categories of observation and there is less inclination to record unforeseen events. Because the approach to observation involved a small number of categories of observation, as well as an openness to record unforeseen phenomena, this meant that the observational approach fell into the semi-structured category.

The consistent laboratory environment allowed a high degree of control with regard to observations. The role of the researcher was close to being a *complete observer* (having no participatory role). Observation is traditionally non-interventionist, with no manipulation of the situation or prompting of questions (Adler and Adler 1994, cited by Cohen et al. 2017). While the classification of the researcher in this study is close to being a complete observer, there was minimal intervention with some participants. This occurred when it was obvious the participant was having a problem, for example with the controls or instructions, and when participants verbalised their thoughts. However, every effort was made to keep intervention to a minimum: the researcher stood back at some distance, was silent where possible, and was not visible while the participant was wearing the HMD.

The observation occurred on participants who played the game continuously to completion over the course of about twenty to forty minutes. This meant notes were ongoing and fragmentary, with additional transcription occurring after the participation. To help with the transcription, additional shorthand qualifiers were added to indicate the stage of participation the participants were at (for example, *L2* for the level two challenge). Once participation was complete, the notes were structured using the form in Appendix A.9. An example of a filled-in form is in Appendix A.10. The stages of participation were added using the stages table on the form.

The semi-structured nature of the observations pre-empted some of the content analysis that followed (see Section 5.3.3.1) and it is debatable whether this was a help or a hindrance. A content analysis usually allows categories to emerge, but as can be seen from the semi-structured observation form, three categories were already in place:

- Usability / accessibility (addressing UDL);

- Strategies employed (to see how the game mechanics and dynamics would be adopted by participants when completing challenges);
- Pedagogical (perhaps the most subjective or interpretive of the three—which observations said something about the way the participants learned).

Bryman (2008, p.260) suggests that the categories in structured (or semi-structured as is the case in this study) observation should be inclusive (with respect to the research questions being asked) and not overlapping.

5.3.1.6 The Questionnaire

The questionnaire (see Appendix A.6) was organized into nine sections as follows:

A Demographic information, including age range, gender, education level, employment status, frequency of video game play, involvement in the education sector, and pre-existing knowledge of graph theory.

B Effectiveness of the game from a learning outcome perspective.

C Effectiveness of the game from a motivation perspective.

D Effectiveness of the game from an efficiency perspective.

E How well the game and platform helped with progression of learning and its visualization.

F How well the game and platform performed from a formative feedback and gamification (extrinsic motivation) point of view.

G How the participants felt about the use of their learner interaction data for various purposes.

H Questions specific to VR.

I How well the game adhered to the checkpoints of the UDL framework.

Sections B, C and D are based on All et al. (2015), which details a conceptual framework for evaluating the effectiveness of a DGBL solution. The framework was devised following a study of practitioners in areas related to DGBL. What emerged was that DGBL was effective when it was successful from the point of view of learning outcomes (stimulation of interest in the subject matter, performance, transfer), motivating players to engage (enjoyment, motivation towards DGBL), and efficiency in comparison to traditional learning methods (time management, cost). Those aspects of the framework that were relevant to learners became questions. Cost efficiency was not of relevance to learners, for example, and was omitted.

Section E's items were concerned with how successful the mapping of learning outcomes (using Biggs's SOLO taxonomy—see Section 2.5.5.3) to the game's learner interaction events was (discussed in Section 3.3). Also of relevance were the sections on learning analytics dashboards (2.8.1.1) and metacognition (2.5.4).

The questions in section F were devised with reference to what the literature revealed about feedback (one of the seven principles of effective teaching and learning according to Chickering and Gamson 1987) and how gamification can create extrinsic motivation (Section 2.3.3.3)

Section G was informed by the review of learning analytics in Section 2.8.

The items in section H were informed by both the review of VR in Section 2.4 and the discussion of universal design consideration in Section 2.7.

The items in section I were devised following a review of the thirty-one checkpoints in the UDL framework, discussed in Section 2.7 and Section 4.5. Also consulted were sections on metacognition (2.5.4), learner preferences (2.5.2), VR (2.4) and flow and balance (2.3.3.2).

The individual items are discussed further in Section 5.3.3.3 as the questionnaire data is analysed.

5.3.1.7 Data Analysis

The exact methods of data analysis are explained in Section 5.3.3. However, it is important to discuss the approach to data analysis and how it fits into the larger study methodology. While the study is a mixed methods one and involves both quantitative and qualitative methods, the qualitative methods have taken precedence: a purely quantitative approach would have dictated larger sample sizes and a faster throughput of participants (for example, unobserved and in parallel), whereas the qualitative approach dictated that a smaller sample size and slower throughput would be necessary. Thus, it could be said that the quantitative methods were subservient in some ways to the qualitative methods. It appeared unlikely that a purely quantitative approach with the sample sizes used would yield many results that were statistically significant, instead perhaps hinting at some findings that required further research. But what the results of the quantitative aspects of this study do provide are a way to, in some ways, address what are often cited as some of the limitations of qualitative research.

The following list summarises the critique of qualitative research in Bryman (2008):

- It is too subjective.
- It is difficult to replicate: whereas a survey or computerised data collection instrument can just be re-run, in qualitative research the researcher *is* the data collection instrument and when you change the researcher, subjectivity and interpretation can lead to different results.
- It can lead to problems with generalisations: how can a small number of, albeit high quality, participants or cases be representative of a wider population?
- There can be a lack of transparency: it can be difficult to discern exactly what a researcher did to arrive at certain conclusions.

With that list in mind, the use of quantitative methods serves as a way to bolster the results of the qualitative analysis, by way of triangulation, as discussed previously.

5.3.2 Data Cleaning and Preparation

5.3.2.1 Gameplay Data

According to Chu et al. (2016), "[d]etecting and repairing *dirty* data is one of the perennial challenges in data analytics, and failure to do so can result in inaccurate analytics and unreliable decisions". Therefore, the cleanliness of the data captured by the API needed to be examined and dirty data removed. The structure and format of the data and how the data was generated and stored was discussed in Section 4.3.1. The data was stored in a MySQL relational database. Some cleaning of the data in the database was necessary before queries could be run reliably.

Of the 20 participants in the study, gameplay data was captured for 19. A communication error between the game and the API resulted in one of the participants not being properly logged in and the issue was not apparent until data was checked immediately after the gameplay ended. A hotfix (a code fix that is manually made outside of the normal software development release cycle) was immediately put in place to ensure that where a connection error occurred, a default login would be used to ensure gameplay data was recorded, with some minor clean up after to assign the data to the correct learner. Thankfully, there were no further connection errors.

To ensure that only valid participant data was to be analysed, an SQL query was executed to delete all learner interaction data that did not belong to the participants (see listing in Appendix D.5.1.1), such as test run data generated between participations when verifying the DGBL solution was operating correctly.

Other checks were performed to ensure the consistency of the data. For example, while there were 19 *tutorial_end* keys in the audit trail, there were 20 *tutorial_start* keys. On further analysis participant B had started the game twice. The observational notes for the participant were consulted and a note had been taken that the participant had "pressed Oculus button - game restarted". The participant had accidentally pressed a button (the Oculus home button) that takes the player out of the game and into the Oculus application. The game was restarted 3 minutes after the game had previously started. The 4 learner interactions stored for participant B prior to restarting the game were manually deleted using MySQL Workbench.

Another example was a minor bug in the software at the end of the game where repeated pressing of the A button resulted in the *graph_complex_rule* key being stored repeatedly. Duplicates of the key after the first instance were manually deleted for the 10 participants where this happened.

With the data cleaning complete, it was then possible to continue with an accurate analysis of the captured gameplay data.

5.3.3 Findings

5.3.3.1 Content Analysis of Observational Data

5.3.3.1.1 Overview

Graneheim and Lundman (2004), when discussing qualitative research that is based on narrative and observational data, write that it:

> requires understanding and co-operation between the researcher and the participants, such that texts based on interviews and observations are mutual, contextual and value bound.

This leads the authors to state that their presumption is that a text (which would include the observational notes taken as part of this study) has “multiple meanings” and involves “some degree of interpretation”.

Prior to beginning the observations, four broad categories had already been determined:

1. Issues encountered by players from a ‘UDL’ perspective
2. ‘Strategies employed’ to complete challenges
3. ‘Pedagogical’ observations
4. ‘Other’

A thematic analysis was performed on the observational notes under the four categories using the approach outlined in Graneheim and Lundman (2004), which is widely cited and was based on a wide-ranging examination of literature on qualitative content analysis. A thematic analysis is an interpretive process where not just manifest content is examined, but also latent content (Bryman 2008, p.282). The approach of Graneheim and Lundman can be described as *Big Q* thematic analysis in the sense that a researcher, like a sculptor, chips away at a block of granite until what is left, the sculpture (findings), is the result of an interaction between the sculptor (researcher), their skills (the ability to analyse and interpret) and the raw materials (observational notes from the learner study or the textual responses to questions in the practitioner study) (Braun et al. 2014). This is distinct from what Braun et al. call *little q* thematic analysis, which is more quantitative and often relies on the development of a codebook to apply to the remaining dataset.

In outlining here the steps involved in the content analysis, terminology explained in Graneheim and Lundman (2004) is used (and emphasised). The observational notes were examined for both *manifest* content and *latent* content—the former being what is obvious and the latter what is inferred; there is a level of interpretation in both, but more with the latter. The content was searched for *meaning units* (words or phrases relating to a central meaning), *condensed* where necessary, and then the higher-order headings were *abstracted*-—codes, categories and themes.

Brenner (1985) calls the condensing, excising and reinterpreting of data "culling". He also writes that it is impossible to report everything that happened and so the researcher must be selective. A code is a label given to a piece of text (or meaning unit) to denote the idea or concept contained therein. This means that though two or more pieces of text may have different words, they may be labelled with the same label because the meaning is the same. Labels can be decided in advance or be in response to the textual data collected (Cohen et al. 2017).

The process of coding is not without critics. Cohen et al. (2017, p.673) list a number of potential issues raised in the literature, including: codes can strip important context and lose the bigger picture (the fragments are not holistic); humans tend to look for patterns that do not exist, which coding facilitates; the deeper meaning of a text can be lost in coding; a "vacuum cleaner" approach can lead to all codes being treated equally when some will be more important than others and could be a symbol of textual data that is theoretically rich.

The issue of context stripping is addressed here. The observational method was just one part of a whole, a mixed methods approach. The capture and analysis of gameplay data, as well as the filling in of questionnaires, allowed data to be gathered on perceived and actual outcomes, for example. At no time during the observational phase of each participation were notes taken on time taken to complete an exercise, because the captured gameplay data was going to be analysed and those statistics calculated. It would be an easy mistake to make, when looking at the observational data in isolation, to determine that the game was full of usability or pedagogical issues. The wider context, however, is that the researcher was specifically looking for usability and pedagogical issues to further improve the game. This means that many positive aspects of usability were not recorded as observations because they did not need to be fixed. Once the questionnaire data was analysed, participants reported strong agreement with statements concerning the effectiveness of the game, and it is only through a combination of all methods that the full picture emerges.

Table 5.1 shows an example of how some of the meaning units under the ‘strategies employed’ category were condensed and then coded.

Table 5.1: Examples of the coding performed.

Meaning Unit	Condensed Meaning Unit	Code
(T) Initial problems with selecting then connecting	Did not figure out teleport mechanic initially	Delayed Learning of Mechanic
(E3) Moved vertices closer to each other to see them in the same frame	Moving vertices into proximity	Proximal Arrangement
(O - throughout) Teleports with cubes to bring them closer together, all in the viewport / frame	Bringing vertices closer together	Proximal Arrangement
(E2) Raise of rodent vertex – “Easier when cubes up at different level”	Lifting to aid visibility	Lifting
(T) Grabbed vertex too early – issue of depth perception it seemed	Grabbed in front of vertex	Depth Perception Issue
(E1) Could have used feedback in tutorial – was not quite sure of whether was finished or not	Game did not update on progress	Lack of immediate feedback

An example of probing deeper for latent content is the observation that participant F was “spending a lot of time with the examples”, which was coded as “high engagement”. Other examples include “fantastic” (novelty), “it’s a different world” (novelty, presence), “interesting effect” (novelty) and “too far away initially to grab” (depth perception issue).

5.3.3.1.2 The ‘UDL’ Category

The primary purpose of making observations under the UDL category was to discover issues to resolve rather than identify themes (as it happens, the overall theme of ‘Usability’ overarches the discussion in this section). The UDL observations were key to the iterative approach of the AMDGBL and the formative evaluation phase. Rather than wait until the end of the study, the observational notes were examined for issues to resolve (or to examine the success of the game from a usability standpoint) after each iteration. Nielsen (2000) recommends just five users in a usability test and to iterate frequently with more five-user tests. This is similar to the approach taken for this study: there were three iterations of 7, 7 and 6 participants, with usability issues resolved after each iteration (during the following sprint).

As previously noted, not all codes are created equal and the following analysis can be viewed through that lens. However, it is notable that there were significantly more observations concerning usability in the first iteration (participants A to G) than the second iteration (participants H to N), both with seven participants. By addressing many of the issues discovered in the first iteration, there was a significant reduction in the number of observed issues, such as those concerning “lack of instructional clarity” and all issues related to floating text (text that was fixed to the player’s viewport and moved in unison with the player’s head movement) were eliminated.

By the time the study had reached the final iteration, most issues had been resolved, though two particular participants presented unique (with respect to the overall sample) usability issues. The first was self-reported dyslexia (participant O volunteered this information as part of the think aloud protocol) which meant that the participant occasionally mixed up the left and right controllers. This led to a recommendation that the next iteration of the game fully mirror the mapping of controls on both controllers (they were largely mirrored with the exception of the A button on the right controller, which was used for the connection mechanic—this could easily be mirrored with the X button on the left controller). The second issue was height: participant S was significantly shorter than the other participants in the study and had an issue with perspective; many of the vertices were blocking each other from the participant’s lower perspective, making it difficult to get a high-level overview of a graph to complete.

While both cases are outliers, they are not significant outliers. The CDC in the United States published a growth chart[2] showing that 10% of women aged 20 years were 5 foot 1 or shorter. The prevalence of various forms of dyslexia is of similar significance (Sprenger-Charolles et al. 2011).

Does this mean that the three iterations and the 6 or 7 participants per iteration were not enough? A pragmatic answer to that question is that the approach could not hope to identify every possible issue, but it can identify the great majority of them as suggested by Nielsen (2000). In addition, a frequently-cited article by Guest et al. (2006) illustrated that in a study

[2] https://www.cdc.gov/growthcharts/data/set2/chart-08.pdf

featuring 60 participants (from a homogeneous group), 92% of the codes had been discovered by the time participant 12's data had been processed; this meant that the remaining 48 participants only accounted for 8% of the codes. This illustrates that there comes a point where continuing a study enters a period of significantly diminishing returns (one could argue it is like falling off a cliff). Summative evaluation can later be used to identify outlying issues and resolve them in a future iteration.

Two categories were identified after coding the UDL data: orientation prior to the game and usability design issues in the game itself. Iteration 1, in particular, highlighted several usability issues that could have been avoided with a more comprehensive orientation. Table 5.2 lists examples of the codes under the two themes.

Table 5.2: Codes under identified UDL categories

Orientation	In-game Usability
Ill-fitting HMD	Lack of Textual Clarity
Accidental Button Press	Lack of Instructional Clarity
Cable Tangling Affecting Balance	Floating Text Issue
Persistent Controller Difficulty	Depth Perception Issue

The orientation category emerged when an analysis of the codes revealed that many of the issues they symbolised were preventable without fixing the game itself. It was evident from observations and reported gameplay experience from the questionnaire, that a significant number of participants were not experienced with playing video games (and by extension game controllers) and VR experience was very limited (these statistics are discussed in sections 5.3.3.3.8 and 5.3.3.3.9). Therefore, it is appropriate to spend a significant amount of time orienting each learner prior to playing for the first time. Orientation time was increased for iterations two and three and there was a noticeable decrease in the number of preventable usability issues.

5.3.3.1.3 The 'Strategies Employed' Category

Some shared behaviour was observed in all participants while they were completing challenges, that of following the rules of the graph and connecting the vertices using the mechanics taught during the tutorial level. Of the 20 participants, 11 of them employed no additional strategies beyond employing the standard locomotion and vertex connection mechanics (in other words, they did not physically interact with the vertices), and for many of these no observational notes were taken under the strategies employed category. However, with 9 of the participants, additional strategies were observed.

When coding was complete (having first condensed the meaning units), three codes were removed from the strategies employed category: *methodical* and *trial and error* (these were deemed to be more appropriate to the pedagogy category and were moved there), and *standard*, which was another way of saying there was no strategy beyond standard locomotion and vertex connection. This left the three strategies below.

Proximal arrangement: Four participants grabbed vertices and moved them to a more central location where they could see them more easily. This involved teleporting to a vertex, grabbing it and teleporting to the central location. In one extreme case a participant moved all vertices in a graph into a very small space so that all of them could be seen within the player's viewport (all vertices could be seen in a single glance).

Lifting: Five participants rearranged the graph to make it easier to see relationships between the vertices. For example, some of the vertices were elevated (by grabbing them and raising the hand) so that there was less overlapping of edges.

Wiggling: Five participants grabbed vertices, raised them and waved or wiggled them about. This had the effect of making the connections to other vertices more obvious as the connections moved.

Table 5.3 shows the frequencies of each code. No participant was observed employing all three, however several were observed employing two of them (four employed lifting and wiggling, one employed proximal arrangement and one employed proximal arrangement and wiggling).

Table 5.3: Codes under the Strategies Employed category

Code	Frequency
Proximal arrangement	4
Lifting	5
Wiggling	5

A single theme emerged from analysing the observational notes under the 'strategies employed' category: *Learner Autonomy*. Section 5.3.4 includes a discussion of how the evidence of a variety of strategies employed shows that learner autonomy and open inquiry were supported by a range of factors, such as the design and implementation of mechanics and dynamics, and the sense of presence, spatialisation and proprioception afforded by the VR environment.

5.3.3.1.4 The 'Pedagogical' Category

The pedagogical observations concerned the way in which learners learned during the game. Four broad themes were identified: Learner Experience, Learner Engagement, Quality of Instruction, and Learner Approach. The codes were categorised and these categories grouped under the aforementioned themes. Tables 5.4, 5.5, 5.6 and 5.7 list the categories and the codes thereunder.

Table 5.4: The 'Learner Experience' Theme.

Category	*Immersion*	*Novelty*	*Learner Preference*	*Balance*
Codes	Presence	Interesting	VR Suits Visual Learning	Frustration
	Complete Immersion	Fantastic	VR Suits Learning Preference	
		Novelty	VR and Visual Learning	
		Cool	Hands Help Cognition	

Table 5.5: The 'Learner Engagement' Theme.

Category	*Engagement with Examples*
Codes	Low Engagement
	Moderate Engagement
	High Engagement

Table 5.6: The 'Quality of Instruction' Theme.

Category	*Feedback*	*Instructional Quality*	*Relevance*
Codes	Lack of Immediate Feedback	Too Technical	True
	Needed Feedback	Issue with Instruction	Makes Sense

In examining the themes, categories and codes (and the underlying meaning units), the following observations could be made:

Table 5.7: The 'Learner Approach' Theme.

Category	*Strategic*	*Response to Adversity*	*Ignoring*
Codes	Methodical	Trial and Error	Ignored Instruction
	Practice		
	Reading Aloud		
	Deep Concentration		
	Quiet		

- The game immerses the learner in a novel environment that stimulates their interest and supports their preference for how to learn. However, there are issues of balance with occasional frustration that could be addressed by giving learners the option to quit out of an exercise.
- A wide range of engagement was observed, with high engagement supported by the real world examples if learners were inclined to spend time examining the examples.
- The quality of instruction was good, particularly in terms of relevance, but there were some minor issues regarding confusion due to unclear instructions, instruction at too technical a level, feedback, and guidance, such as letting the learner know they were finished a challenge or that what they were looking at was an example and not an exercise. The latter relates to the concept of *guided participation* (Rogoff 1990)—a game must be capable of guiding the learner through the game because there is usually no human intervention to nudge the learner back on track.
- The game allowed learners to approach their learning in various ways, such as being methodical (or deeply concentrating), practising until comfortable and reading aloud (or being silent). The challenges in the game saw some learners respond to adversity by engaging in trial and error to find a solution. Occasionally, learners clearly ignored instructions.

As discussed in Section 5.3.3.1.2, a limitation of the observational notes is that they tended to focus on what was going wrong rather than going right, due to the mixed methods approach and leaving the positive aspects of the game to the analysis of questionnaire and gameplay data. Both showed some very positive outcomes from a pedagogical standpoint, as discussed in later sections.

5.3.3.1.5 The ‘Other’ Category

The ‘other’ category was a catch-all for observations that were initially difficult to categorise. Some of the observations were re-categorised (for example the observation note:

> ‘Cool’ – in response to grabbing vertices + ‘Oh God’

was moved to ‘pedagogical’). Some were notes to the researcher, such as the researcher noticing a typographic error, or observing that English was not the first language of a participant (this observation is used in Section 5.3.3.2.4 to explain why a participant had a fundamental difficulty with exercise 3, which required a good knowledge of the English language).

Some observations were difficult to categorise. The observation that a learner was experimenting with the environment by seeing how vertices could be made to overlap, could be seen as the participant being playful and therefore contributing to learning; for example, an attribute of *open inquiry* would be testing the boundaries of what is possible in the environment, something that is fundamental to “doing science” (Colburn 2000).

The ‘other’ category was also a place to record notes about participant attitudes. One participant was visibly annoyed with exercise 3, disagreeing strongly that “wagon” was a synonym of “cart”, despite many other participants connecting the two words early in their effort (and no other participant voiced a disagreement about the synonyms in exercise 3).

5.3.3.2 Analysis of Gameplay Data

The following sub-sections present findings from the analysis of gameplay data. A number of R scripts were used to query and analyse the data, produce statistics (such as mean and standard deviation) and plot the data on charts. Appendix D.5.2 contains a hyperlink to a public GitHub repository where these can be viewed or downloaded. The data in Table E.1 shows the data returned by the SQL queries in the R scripts, which the charts and statistics are based on.

5.3.3.2.1 Gameplay Duration

Gameplay began once the unique learner identifier was entered on the keypad in the virtual world. It ended once the final challenge was complete. The difference in time (rounded to the nearest second) between the *tutorial_start* and *graph_complex_rule* keys in the audit trail was used to plot the chart in Figure 5.3.

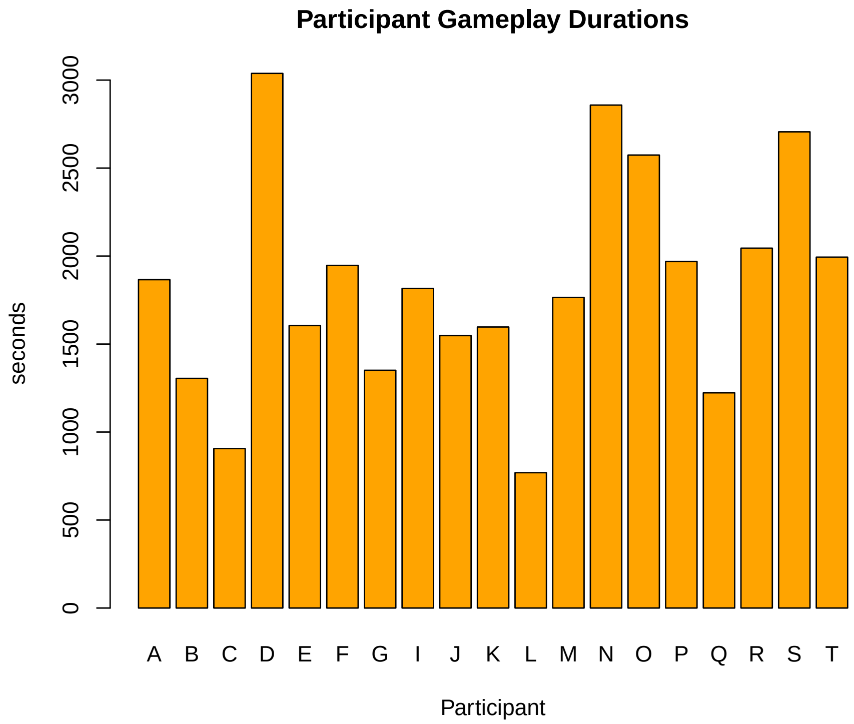


Figure 5.3: Participant Durations

The mean duration was 1835.9 seconds (30:35.9) (*SD* = 622.97 seconds (10:22.97)). The median duration was 1816 seconds (30:16).

5.3.3.2.2 Engagement with Examples

There are two real-world examples presented to the learner at the beginning of level 2 (a social graph and a natural language processing graph). The gameplay data can tell us something about how the learner engaged with them. For iteration 1, only the time taken to progress through the examples was recorded. For iterations 2 and 3, other metrics were gathered: number of teleports and number of vertex grabs (see Table E.2). These other metrics capture some information about how the participant engaged with each example, moving about and manipulating the graph. Figure 5.4 shows total time in seconds that the participants took to progress through the examples.

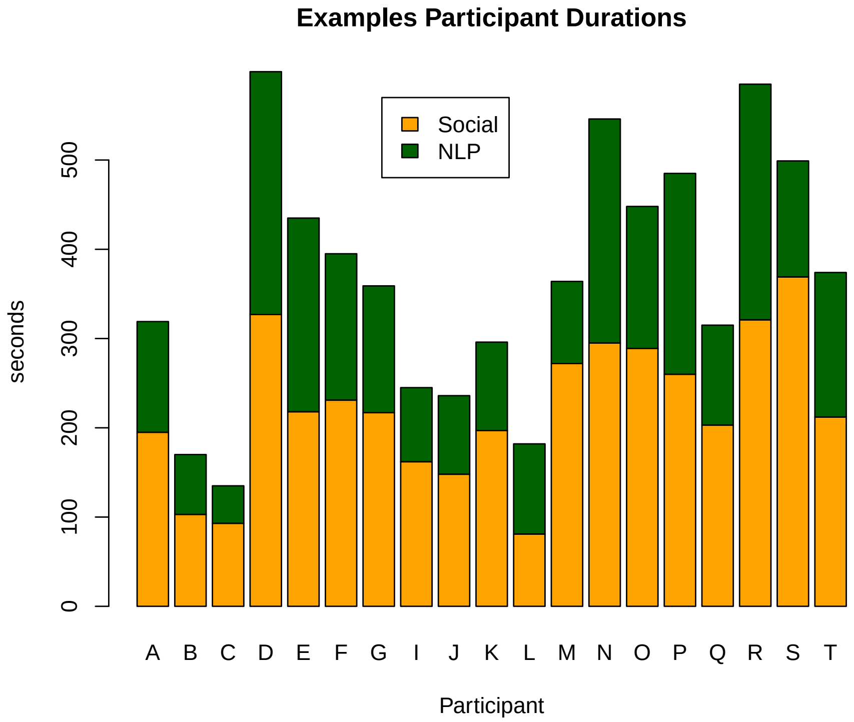


Figure 5.4: Participant Example Durations

The mean duration for the combined examples was 381.3 seconds (6:21.3), with a standard deviation of 131.1 seconds (2:11.1). The median duration was 369 seconds (6:09).

Figure 5.5 shows, for each participant, the total duration in seconds going through the 2 examples alongside the total number of teleports and vertex grabs (total engagements). The total number of engagements was increased by a factor of 9.75 (to equalise the largest number of engagements and duration for participant R) to improve the visualisation.

The mean number of engagements was 16.5, with a standard deviation of 14.9. The median number of engagements was 10.

5.3.3.2.3 Overall Exercise Performance

Figure 5.6 shows grouped exercise durations for each participant.

The mean total exercises duration was 907.6 seconds (15:07.6), with a standard deviation of 311.3 seconds (5:11.3). The median total duration was

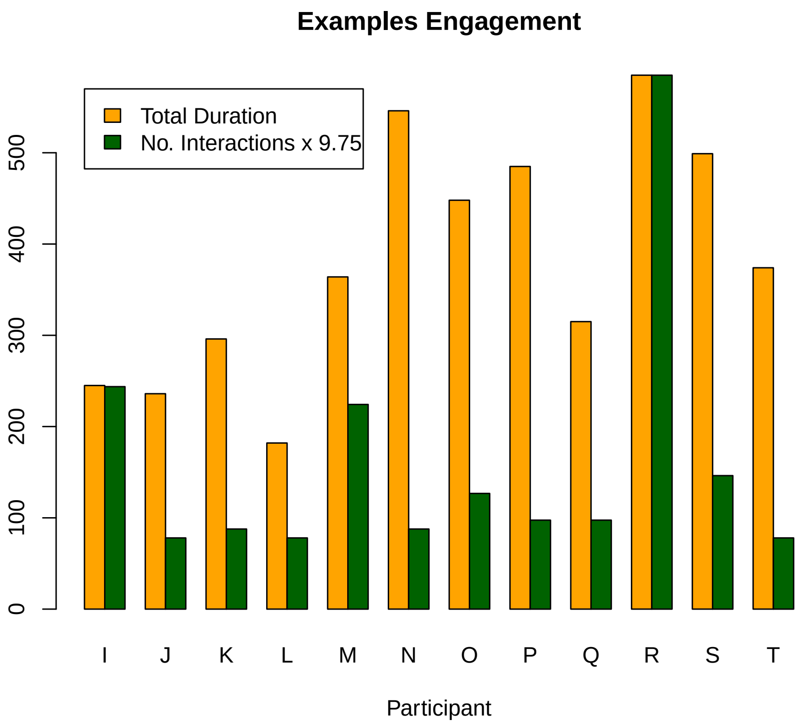


Figure 5.5: Examples Engagement

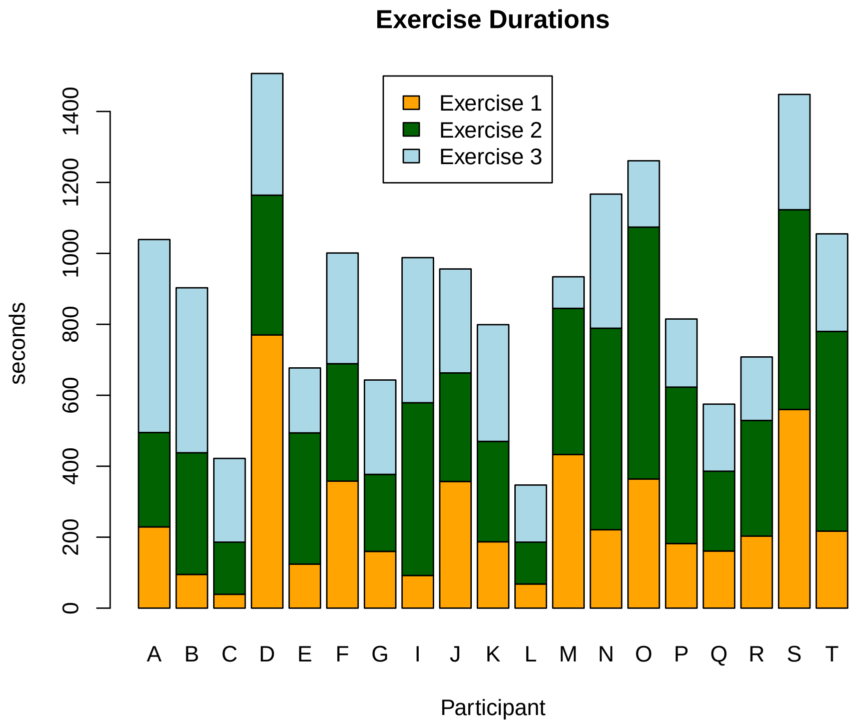


Figure 5.6: Exercise Durations

934 seconds (15:34).

5.3.3.2.4 Individual Exercise Performance

While learners solved the challenges in the game, the number of correct versus incorrect number of edges was captured, as was the connection or disconnection made. For example, when the learner connected the words *Shopping* and *Cart* in exercise 3, the correct count increased by 1 and the value *Shopping:Cart* was stored in the audit trail with the key *toggle_connect:Level3*. To continue that example, if the number of correct edges had changed from 5 to 6 and there were still 2 incorrect connections, a value *6:2* was stored in the audit trail with the key *level3_exercise* and a timestamp.

For each participant, the number of correct versus incorrect edges was plotted against elapsed time in seconds. Three examples are discussed here.

Figure 5.7 shows participant M's performance in exercise 3 (which begins with no connections and requires 9 correct and 0 incorrect connections to complete), with a quite linear progression of correct connections and no incorrect connections. Figure 5.8 shows very quick progression initially, but thereafter a struggle to complete the exercise. Figure 5.9 shows participant T's performance, with a less linear progression of correct connections and a very noisy incorrect line throughout.

There is not much to be said about M's performance in exercise 3. As can be seen from Figure 5.6, M completed exercise 3 in the quickest time and was the only participant to be awarded the *Speed King* badge.

What is interesting is a comparison between the performance of L and T. While a quick glance might suggest there is little between them in terms of the shapes of the lines or how noisy they are, there is a subtle difference. T's incorrect line is noisy from very early on, beginning with only 1 correct edge out of 9. L's incorrect line becomes noisy from a later stage when 6 out of 9 edges were correct—this was the quickest of any participant to get to 6 correct.

Though somewhat interpretive when looking at the data alone, a judgement could be made that T struggled immediately with the exercise and had a fundamental issue, while L had no issues understanding the problem and how to solve it, but quickly lost confidence and resorted to *trial and error*. An incorrect line that is shaped like a saw is indicative of trial and error or

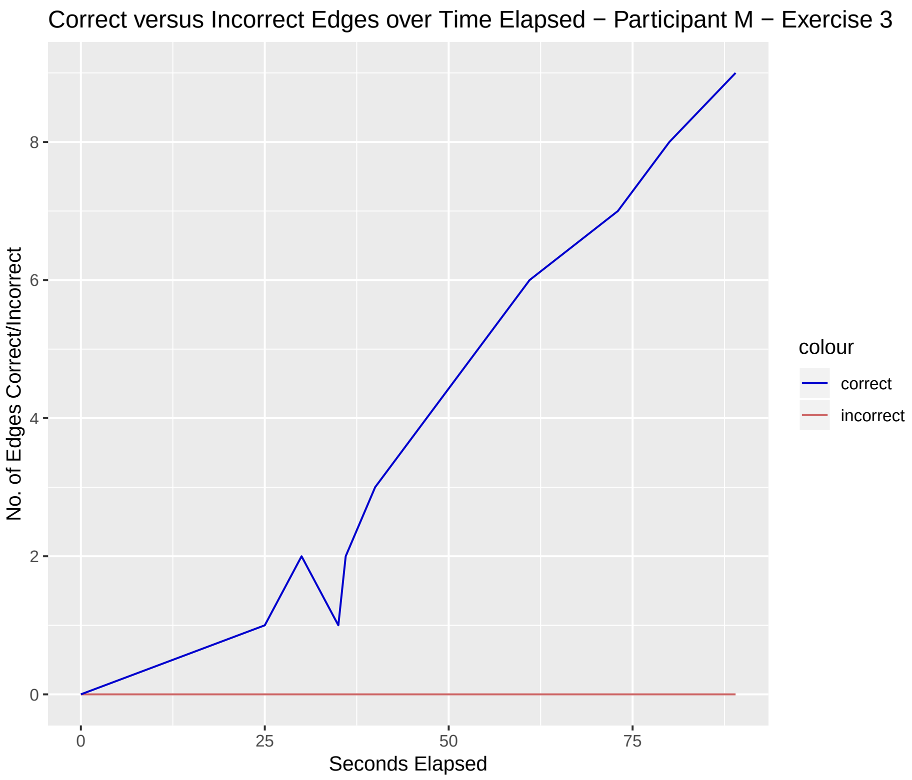


Figure 5.7: Exercise 3 Performance - Participant M

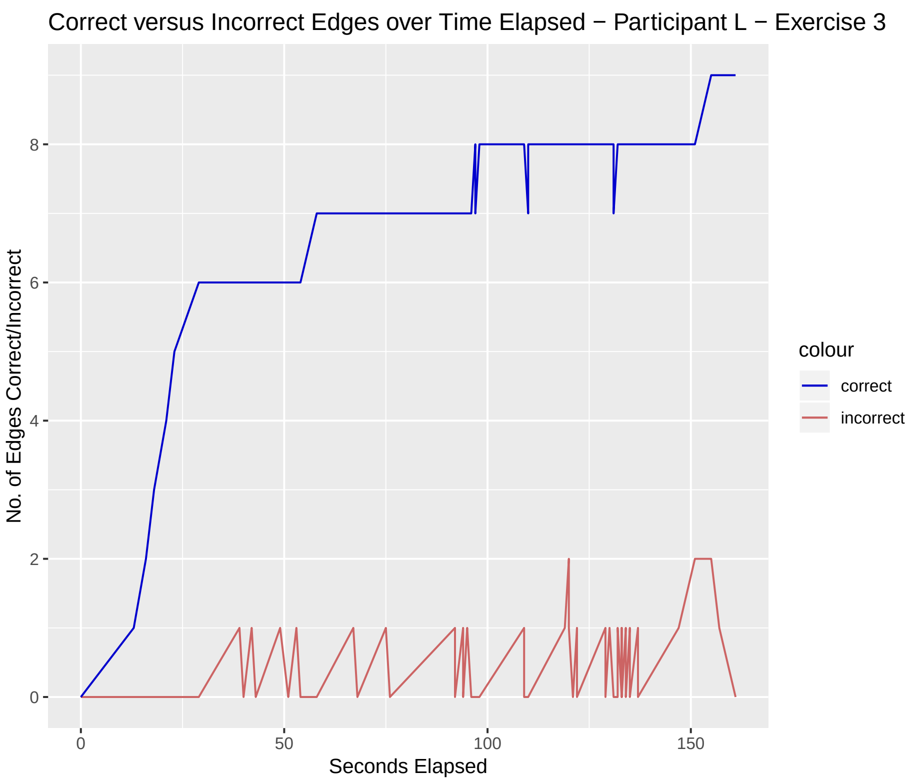


Figure 5.8: Exercise 3 Performance - Participant L

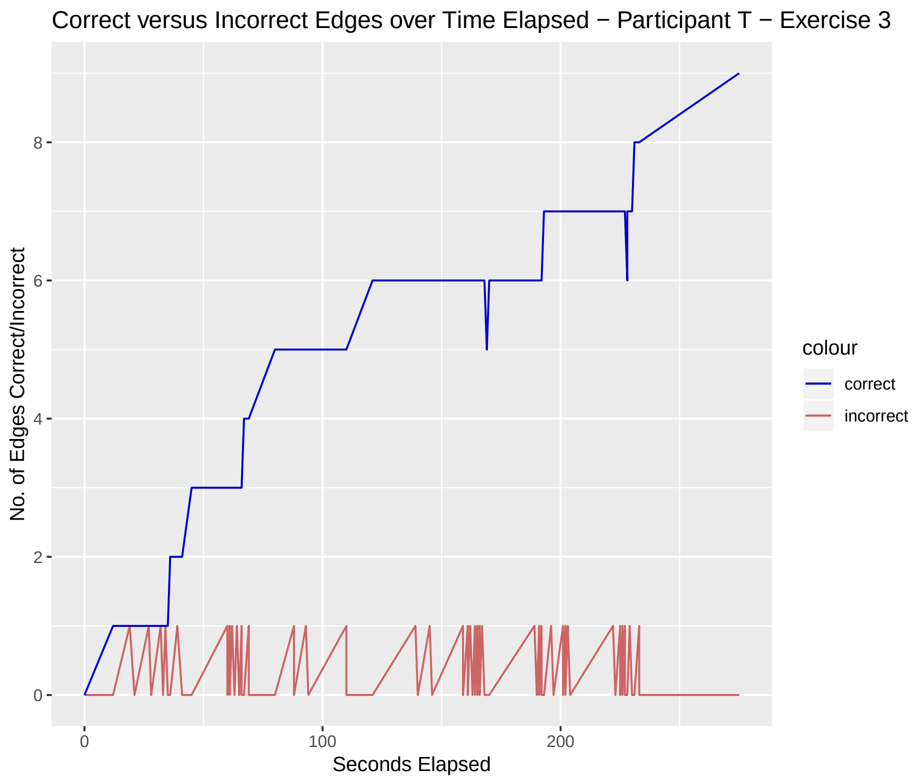


Figure 5.9: Exercise 3 Performance - Participant T

guesswork, something that was confirmed by observations during the exercises and discussions with participants when showing them their exercise performance in the dashboard.

What was also confirmed was that T did have a fundamental issue, which was a language issue. English was not the participant's native language and so the synonyms and phrases proved challenging.

5.3.3.2.5 Comparative Exercise Performance

Each participant was also compared to the average performance. The average was calculated based on the average time it took for learners to get to 1 correct, then 2 correct, and so on.

Figure 5.10 shows the performance of S compared to the average. After a bad start, S appears to figure out the challenge and then progresses at a rate similar to the average.

5.3.3.2.6 Gameplay Data from a UDL Perspective

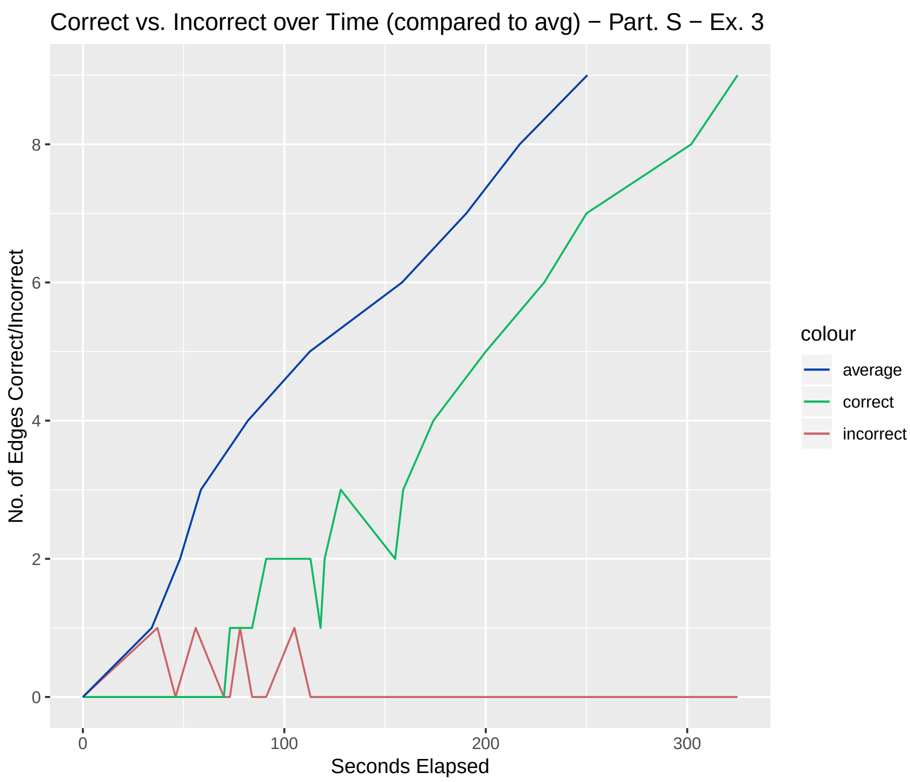


Figure 5.10: Exercise 3 - Participant S - Compared to Average.

The tutorial level gave learners the opportunity to become comfortable with the game's controls and mechanics. A number of timestamps were recorded in the audit trail for events that occurred in the tutorial level. This includes the first occurrence of a: teleport, gaze at a vertex, selection of a vertex, creation of an edge and grab of a vertex. These happen in sequence and the duration between them can indicate whether there might have been an issue—again, the data cannot in isolation be used as a diagnosis of an issue, but can indicate something requires further investigation.

Figure 5.11 shows the individual learner durations, in seconds, of the five main tasks to be completed during the tutorial.

Figure 5.12 is a box plot that shows the five game mechanics taught during the tutorial level and their interquartile ranges, outlier ranges and specific outlier points.

Figure 5.13 is a violin plot that shows the kernel probability density of the 5 game mechanics.

While Figure 5.11 could be used to analyse how quickly individual learners mastered the game mechanics and where individual learners had issues, both

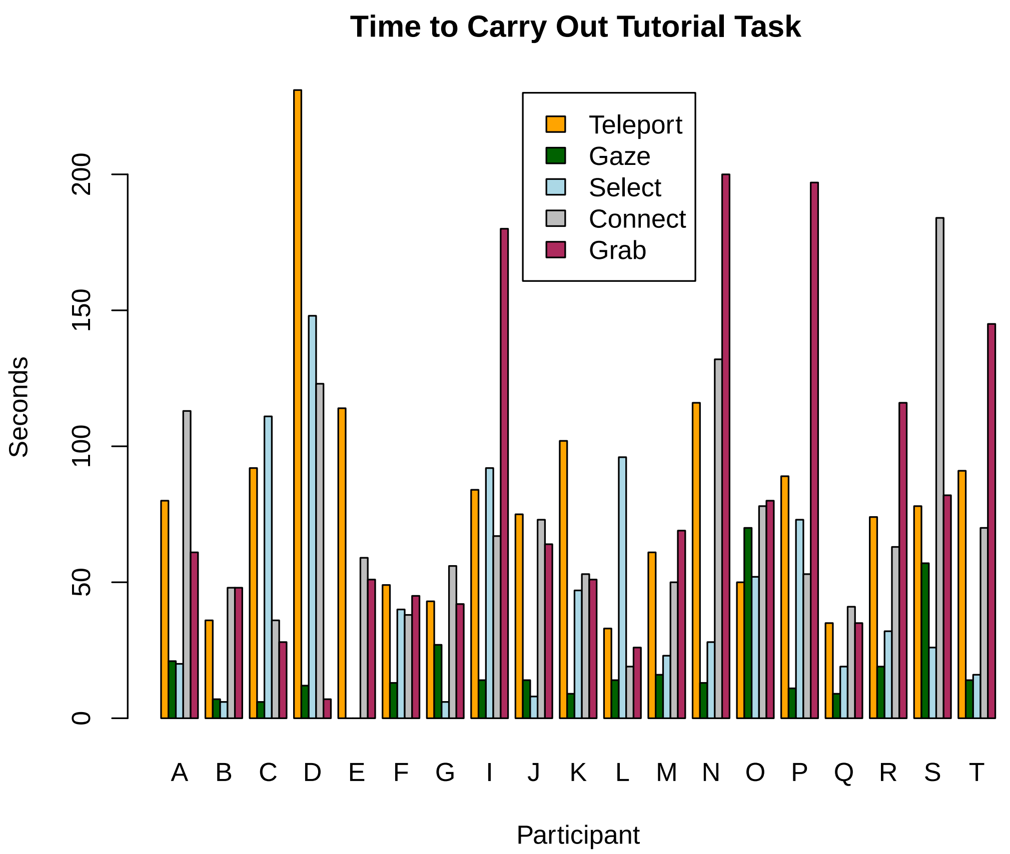


Figure 5.11: Individual Tutorial Task Durations

Figure 5.12 and Figure 5.13 can be used to analyse how the learners as a whole fared with mastering the game mechanics. The gaze mechanic has a narrow distribution of durations, while the grab mechanic has a wide distribution of durations. However, it is notable that the gaze mechanic has 2 outliers.

Can the distribution of durations by game mechanic tell us anything? The following observations could be made:

- **Teleport:** A fairly narrow distribution with only a single outlier. Probably nothing to worry about, but there is a question about why the outlier is so much of an outlier at about 5 times the duration of the median.
- **Gaze:** A very narrow distribution should point to a mechanic that is quickly mastered. Having two outliers does warrant a closer look to see if there was an issue, such as the learner being too far from the vertex and not being aware of this.

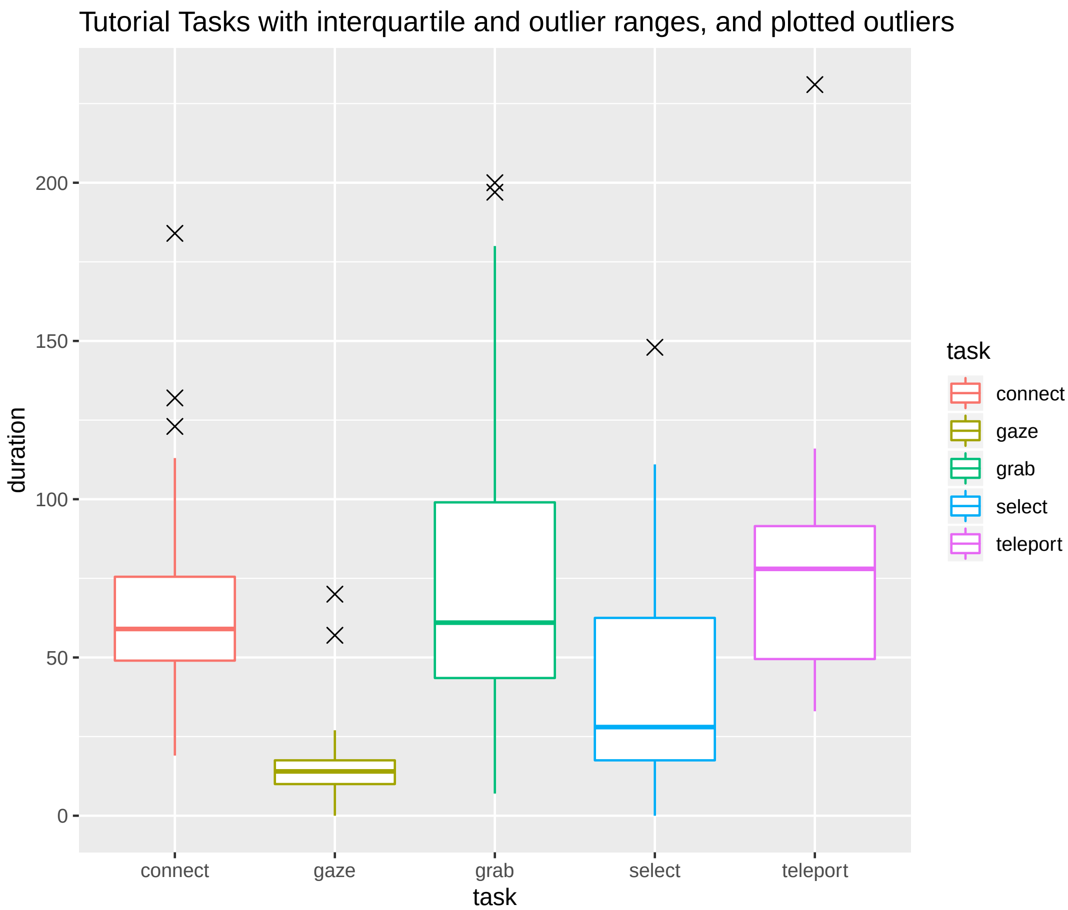


Figure 5.12: Tutorial Task Durations - IQR and Outliers

- **Select:** A fairly narrow distribution, but there are are several durations approaching being outliers (and one outright outlier) and skewing the interquartile range. Most can master selection in under a minute, so why are others having an issue?
- **Connect:** Connecting vertices with an edge requires mastering the gaze and selection mechanics first and wider distribution would be expected versus the gaze mechanic, for example, which requires a head movement (though it might require a teleport to get close enough). The number of outliers is slightly concerning, though, and warrants further investigation.
- **Grab:** A very wide distribution with outliers. Grabbing requires the learner to get close enough to a vertex that their virtual hand can be waved through it. Is there an issue with being able to teleport close enough, or an issue with depth perception?

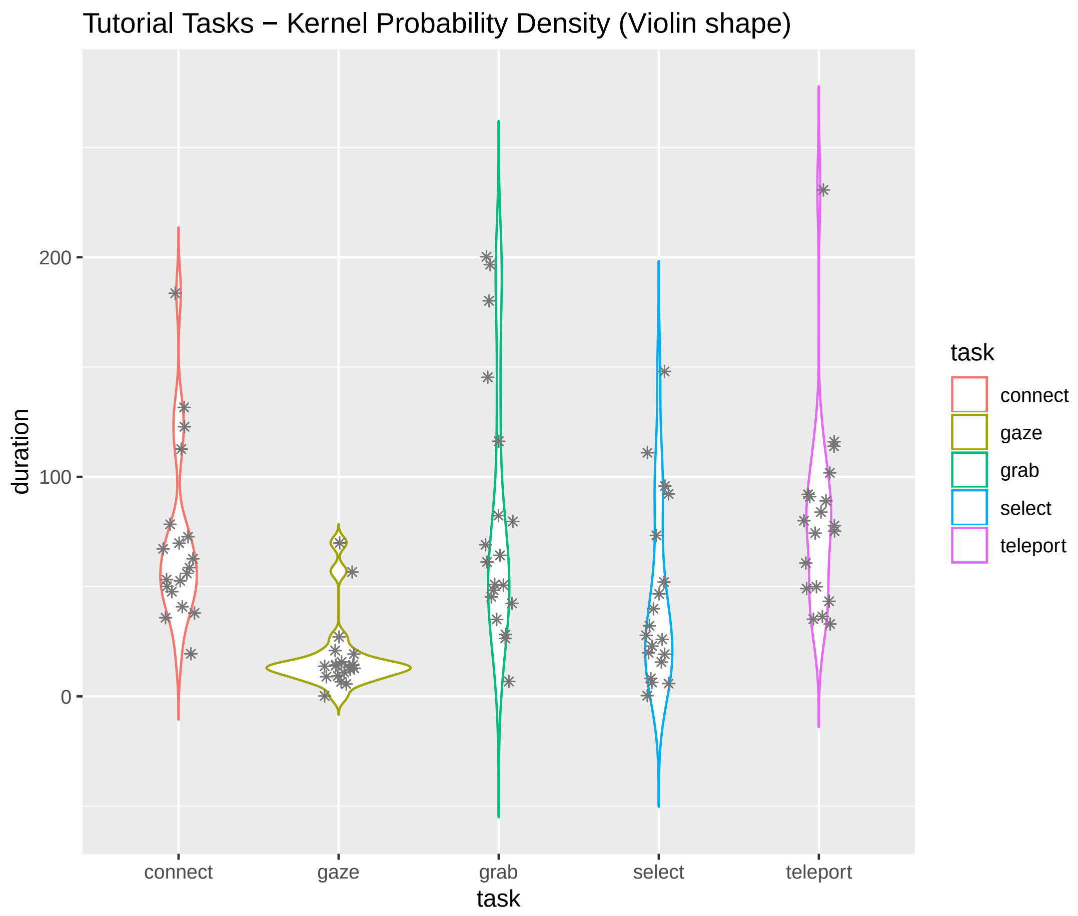


Figure 5.13: Tutorial Task Durations - Kernel Probability Density

Those observations will be returned to in the discussion in Section 5.3.4.

5.3.3.3 Analysis of Questionnaire Data

The questionnaire was almost entirely comprised of Likert scale questions (items). The Likert scale is popular because it offers the researcher nuance compared to binary responses (e.g. liked or did not like); however, they only work properly when the items being measured have unidimensionality (in other words, the statement posed is not double-barrelled, or worse) (Cohen et al. 2017). Therefore, the statements need to be designed carefully. The items were grouped in sections related to certain variables, such as efficiency, motivation, and universal design.

Cronbach's alpha (often called simply the *alpha*) was used to measure the internal reliability of the questionnaire items (Table 5.8). Only the 39 items present throughout each of the 3 iterations of the study were included in the calculation.

Table 5.8: Internal Reliability for Item Groupings

Cronbach's Alpha	No. of Items
0.93	39

A Cronbach's alpha score of 0.7 is considered by many to be the minimum score for reliability, though for some 0.8 or more is considered an acceptable level (Bryman 2008, p.151). Cohen et al. (2017, p.724) suggests a scale where anything below 0.6 is considered to be an unacceptably low reliability, 0.6 to 0.69 is marginal, 0.7 to 0.79 acceptable, with anything above 0.8 considered highly or very highly reliable.

The alpha in Table 5.8 indicates a very high level of internal reliability, providing confidence in the findings interpreted and in administering the questionnaire again in the future, if required.

The following sub-sections present the findings of the questionnaire. Table E.3 lists the item codes, means and standard deviations, as well as the number of participants who responded. Most questions were in the original iteration 1 questionnaire (N=20), with a small number of them in just iterations 2 and 3 (N=13). For the item texts, refer to the questionnaire (Appendix A.6 and A.7).

5.3.3.3.1 Effectiveness Items

Figure 5.14 shows the extent to which participants agreed or disagreed with statements related to the graph game's effectiveness. Section B contained items related to learning outcomes, section C contained items related to motivation and section D had items related to efficiency.

Items B1 and B2 are questions that are focused on the game's ability to teach the fundamentals of graph theory and how well it makes the content relevant to the real world or industry. Participants agreed that it succeeded in both cases (4.0 and 4.3, respectively). B3 is a more subjective question, asking participants to respond to how much their interest had been stimulated in graph theory by the game. While a participant might find the game succeeds in teaching them graph theory and its application, they might not be as positive about their continued interest in the subject. Nevertheless,

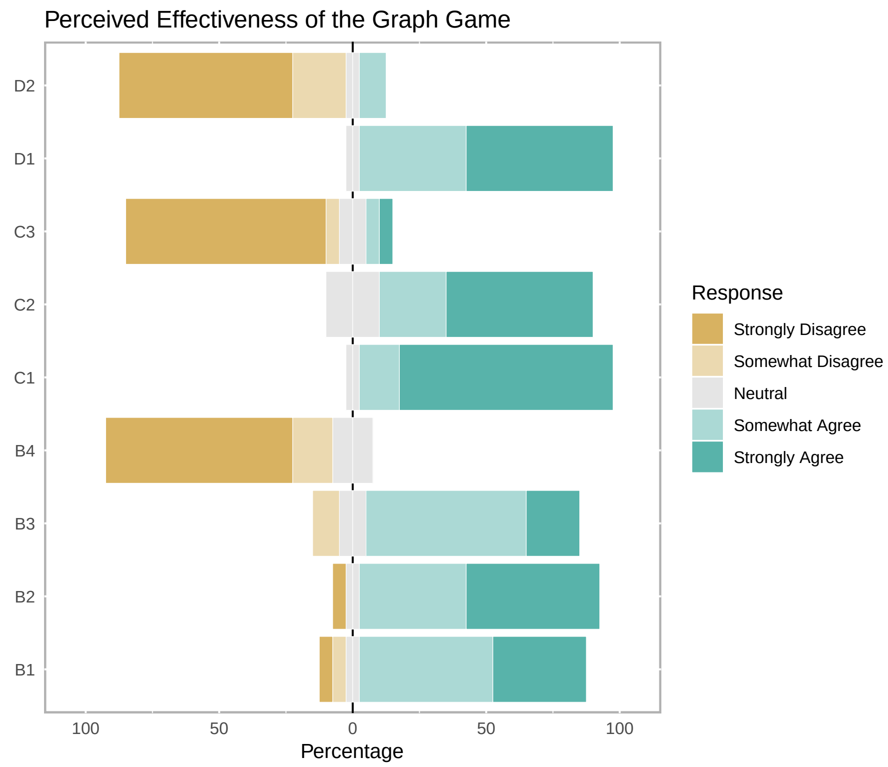


Figure 5.14: Responses to items on Effectiveness (N=20)

respondents still agreed (3.9) that their interest had been stimulated in graph theory. The negative control item, B4 (a double-barrelled question about understanding and application of graph theory), was even more positive for the game with strong disagreement (4.5) that the game did not help participants' understanding or application of graph theory.

Item C1 is focused on enjoyment; participants very strongly agreed (4.8) that they enjoyed playing the game. Item C2 is concerned with motivation to take part in more DGBL based on the experience of playing the game; participants agreed (4.3) that they were motivated to do so. Item C3 was a negative control question asking participants about their likelihood to take part in future DGBL; there was disagreement (4.4) that it was unlikely they would.

Item D1 is about speed of learning and there was strong agreement (4.5) that it was a quick way to learn about graph theory. Item D2 was a negative control question that asked participants if they thought their time would be better spent using other learning resources; there was disagreement (4.4).

5.3.3.3.2 Feedback Items

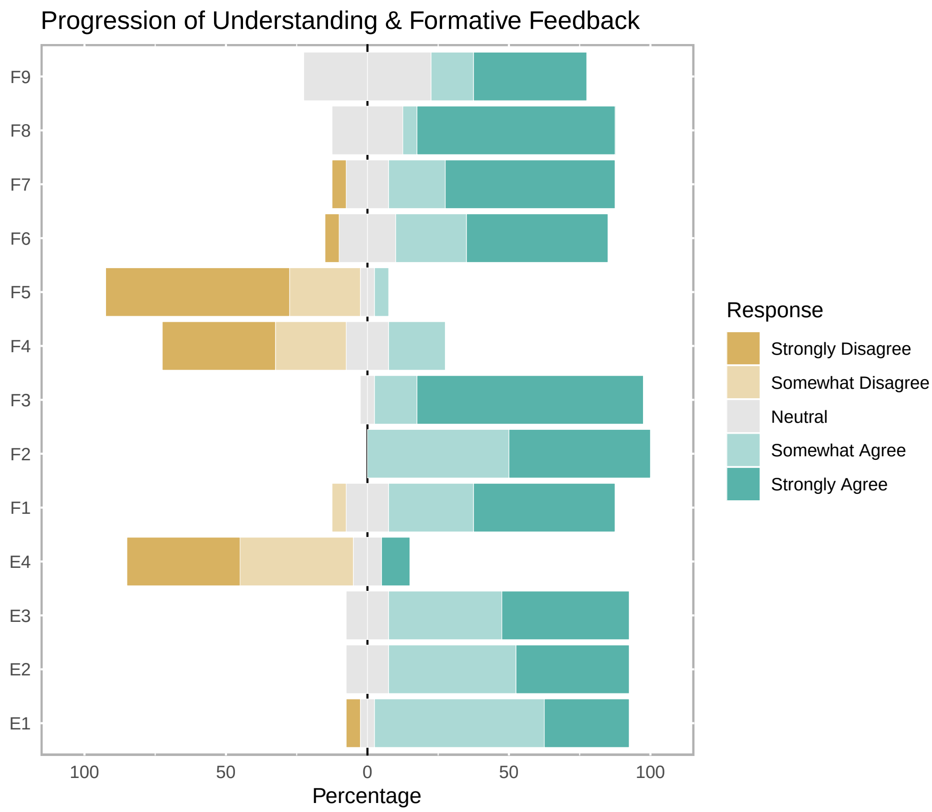


Figure 5.15: Responses to items on Feedback (N=20)

Sections E and F were concerned with feedback. Section E was about progression of understanding, with particular reference to the SOLO taxonomy. Section F was about formative feedback.

E1 asked whether participants thought they had been helped by the game to progress through levels of understanding (simple to complex); they agreed that it did (4.1). The next item, E2, moved to the visualisation of learning progression in the web-based dashboard; there was agreement (4.2) that the visualisation, which was mapped to the SOLO taxonomy, was clear and understandable. There was similar agreement (4.3) with E3 that the visualisation was useful and let them know where they stood with respect to their progression. The negative control question, E4, asked if participants disagreed that they did not have a sense of how they were progressing (not specific either to the game or dashboard) and there was disagreement (4.0) with that.

F1 was concerned with immediate feedback (within the game), whereas F2 was concerned with cumulative feedback throughout the game. There was agreement that the game succeeded with both (4.2 and 4.5 respectively).

Feedback was seen as a key feature of the game. For example, red edges indicated incorrect connections and there were numbers for target, current correct and current incorrect number of edges on a scoreboard. The agreement about the success of the game in terms of immediate feedback was slightly softer than for cumulative feedback. It is possible that where participants became frustrated or stuck with a particular game mechanic, the game did not help them out—the wording of F1 is about doing things correctly, whereas F2 is about how well the participant was doing. A "thing" might be interpreted as any task in the game whether it was learning about graph theory or not.

There was very strong agreement that the leaderboard helped them gauge how they had done compared to other participants (F3: 4.8). That is a clear message that knowing where one stands in comparison to one's peers is important to learners.

It is possible that the leaderboard was a factor in the strength of disagreement with F5 (that the participant had no sense of how they had done after the game) and the softer disagreement with F4 (no sense of how the participant had performed as they played)—4.5 and 3.8, respectively.

One of the primary mechanics of gamification is the award of badges and this is why four items were dedicated to badges. The most straightforward of the four statements asked whether the participant agreed that they found the award of badges motivating—they did agree (4.2). F7, F8 and F9 were more nuanced. F7 asked if participants would retry a challenge just to gain a missing badge (for example, in exercise 3, the award of the *Speed King* badge was dependent on finishing in under 90 seconds, which only 1 participant managed). The participants agreed that they would retry (4.3). They also agreed they would be fine with having other learners view their collection of badges (F8: 4.4), but were a little softer (F9: 4.0) in their agreement that seeing other learners' badges would motivate them to earn more badges (presumably through some form of badge-envy). There were some differences in how younger and older participants viewed badges, which are discussed in Section 5.3.3.3.6.

5.3.3.3.3 Use of Gameplay Data Items

Section G attempted to gain some insight into how participants viewed the use of gameplay data. While the words *ethics*, *opt-in* or *opt-out* were not used in

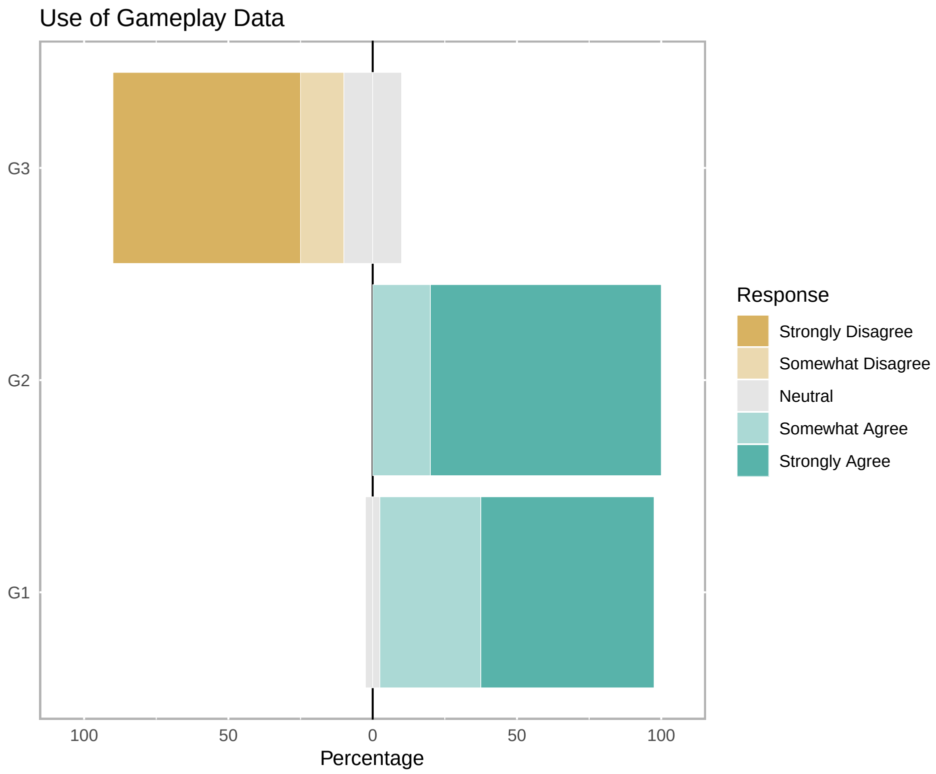


Figure 5.16: Responses to items on Gameplay Data Usage (N=20)

the items, the issue was presented in a roundabout way by asking participants if they would like lecturers to be able to use their gameplay data to see the steps they took in reaching a final answer to an exercise (G3). There was disagreement (4.4) that a lecturer should not be able to see these steps—with no participant disagreeing, it suggests there are little or no ethical concerns with the use of gameplay data for solid pedagogical reasons (other non-pedagogical uses were not explored in the questionnaire).

G1 asked participants whether the visibility of task performance via gameplay data would increase their confidence if it was assessed by a lecturer and there was strong agreement that it would (4.5).

There was even stronger agreement (4.8) that visualisations showing improvements in performance would encourage repetition of exercises.

It was decided that items G4 to G7 would be discarded. It was unclear whether some participants understood that it was only to be filled in by educators. The small number of responses made any findings of significance unlikely. In addition, the second study aims to answer the questions via open questions, which should yield qualitatively better results.

5.3.3.3.4 Virtual Reality Items

H1 asked participants about their prior experience of VR (never, less than 4 occasions, or frequently). Further analysis of the significance of prior VR experience as a factor in the overall questionnaire results are discussed in Section 5.3.3.3.8.

In iteration 1, H2 was a question about preference in the way messages or instructions were presented. The question was added to resolve a user interface issue the researcher struggled with: whether to have floating messages that were fixed in the viewport of the player or to display all messages or instructions on the walls, similar to a projector on a screen in a lecture theatre. The choice is illustrated by two images in the question, as can be seen in Appendix A.6.

Of the 7 participants in iteration 1, 5 selected walls as the place for instructions. One participant opted for no preference. One participant ticked both floating and wall-based messages and wrote suggestions for when either was appropriate:

Floating messages: "Great for quick overview that the user does not need to remember."

Wall-based messages: "Very useful to re-read a task ensuring that it is carried out correctly, but not in the way while carrying the task out."

Based on the responses, the placement of instructions only on walls was implemented prior to the start of iteration 2. The issue is also discussed in Section 5.3.3.1.

The means of identifying whether instructions should be placed on a wall or floated in front of the player is a form of A/B testing (King et al. 2017). A/B testing is used extensively in marketing and user experience design to compare two options, often hyperlinks, to see which receives more clicks.

For iterations 2 and 3, H2 was replaced with new H2 to H6 items. H3 was moved to H7.

Participants were asked if they experienced any discomfort when playing the game (H2 in iteration 1, H7 in iterations 2 and 3). Disorientation or VR sickness is always a concern with VR-based applications (see Section 2.4). 16 participants indicated there was no discomfort experienced. 4 participants indicated some issues.

1. 1 participant ticked *No*, but also entered a message in the *brief description* box: *"Only if it lagged while loading / appeared or if it flashed at an undesirable framerate"*. The no response accompanied by a description of a very mild discomfort suggests that the *Yes* tick box might have been replaced by *mild discomfort* and *major discomfort* tick boxes.
2. 1 participant ticked *Yes* and described a very mild discomfort: "A slight strain on eyes".
3. 1 participant ticked *Yes* and described an issue which may not have caused physical or psychological discomfort, but rather hampered the ability to play the game properly: "Lack of visual clarity of text - some words blocked by beams of light, had to move closer to see text".
4. 1 participant ticked *Yes* and described an issue of disorientation: "Occasionally the environment moved / jittered giving rise to balance issues (momentarily)"

Issue 1 is a typical problem with the VR platform and can be alleviated by a higher specified PC and ensuring a minimum number of running processes. The level loading issue could be alleviated by switching to an empty area with some perspective, such as a meshed floor, and allowing the player to look around while a new level loads. The issue with the view freezing as a new level loads can be quite disorienting.

Issue 2 is not related to the game itself, but rather the Oculus Rift hardware and getting the right fit with the headset. Great effort was made to ensure participants could read text at the beginning of the game. For some participants, issues of focus were an issue throughout.

Issue 3 persisted throughout for the participant. VR platforms, such as Oculus Rift and Vive, have 2 issues that would have hindered the participants view: the *screen door* effect[3] and what are known as *god rays*[4]. Not much can be done about those issues given the limitations of the hardware, but some simple adjustments with lighting in the game and text sizes would have reduced the issues of inability to read text at a reasonable distance.

Issue 4 was related primarily to the placement of the three Oculus sensors. If a player moves out of sight of one or more sensors, the game can lose the

[3]See https://www.howtogeek.com/404491/what-is-the-screen-door-effect-in-vr/ for an explanation

[4]See https://xinreality.com/wiki/God_rays for an explanation

position of hands or even the player. This can lead to a disorienting glitch as the hands or environment move suddenly to the correct position as the sensors re-detect the HMD or controllers.

In iterations 2 and 3, H2 to H6 were concerned with orientation in the VR environment, interacting with the environment, and the learning curve of VR compared to other media. Figure 5.17 shows the responses.

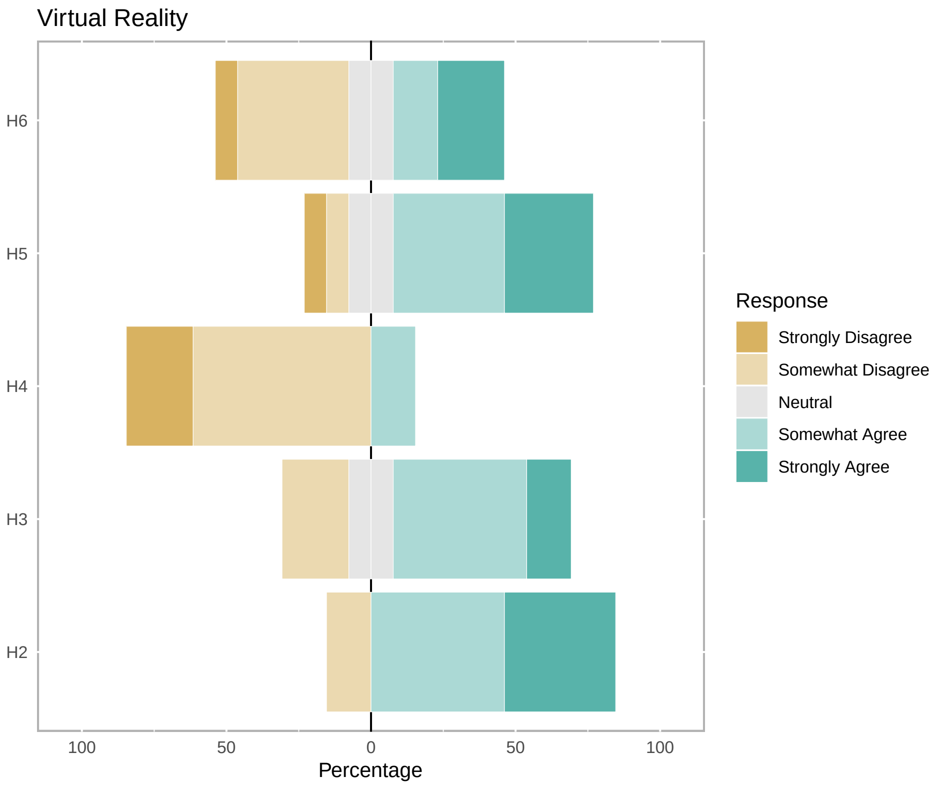


Figure 5.17: Responses to items on Virtual Reality (N=13)

There was agreement (4.1) that the instructions were easy to find (by iterations 2 and 3, they were all wall-based). There was a soft agreement (3.5) that the instructions were easy to read (see discussion of issue 3 above). There was soft disagreement (3.9) that time was frequently spent looking for the next instruction. There was soft agreement (3.8) that once the tutorial level had been completed, there were no difficulties using the game mechanics. The participants were split (3.1) about whether the learning curve compared to other media was steep.

While largely positive in terms of the use of VR and how the game was designed for VR, the sentiment was softer than for other aspects of the game and platform with a wider standard deviation. Therefore, there are clearly some issues to be resolved for the next iteration of the graph game to make the experience more comfortable and less frustrating from a VR perspective.

5.3.3.3.5 Universal Design for Learning Items

The purpose of section I was to determine if the game and platform had ticked many of the boxes (checkpoints) in the UDL framework. All items, except I15, were administered to all participants (see Figure 5.18 for summarised responses). I15 was administered in iterations 2 and 3 (see Figure 5.19). The results of section I are discussed item-by-item with reference to specific checkpoints in the UDL framework v2.2. A formative evaluation as part of the AMDGBL model was performed in Section 4.5 to determine how well the design and implementation of the game adhered to the UDL framework. This section evaluates how well the game and platform performed in terms of UDL from the perspective of the learner (a combination of both evaluations would contribute towards the summative evaluation of the AMDGBL model).

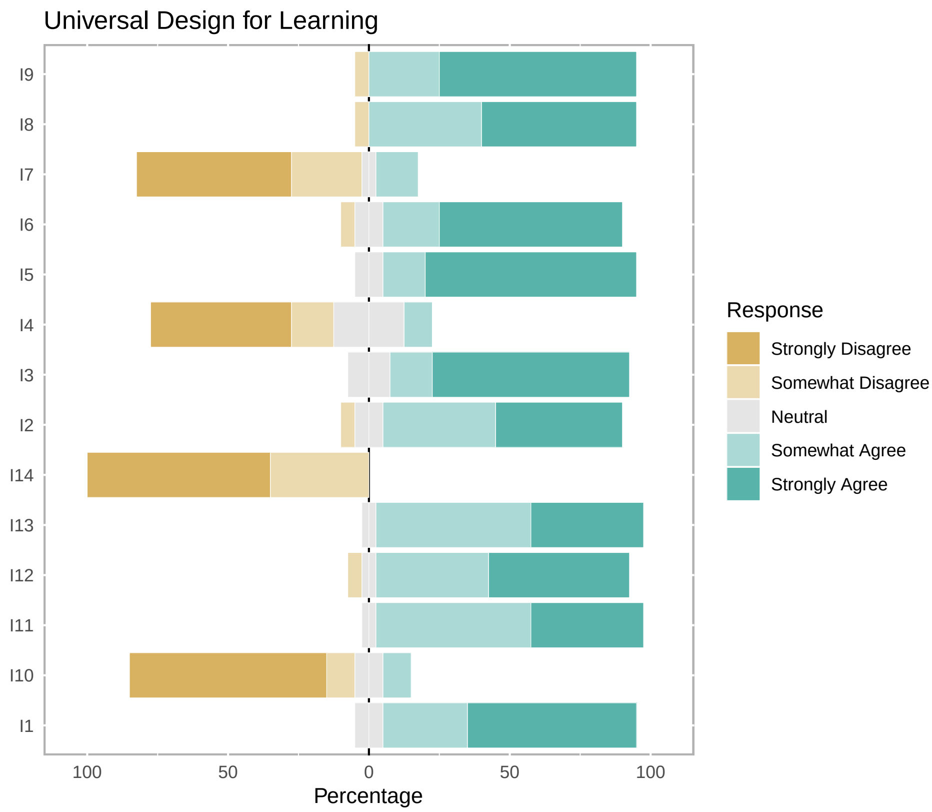


Figure 5.18: Responses to items on Universal Design for Learning (N=20)

I1 and I2 are concerned with using the DGBL-based exercises as assessments towards a final grade (that is, formal assessment). There was strong agreement (4.5) that the exercises could be used for formal assessment and

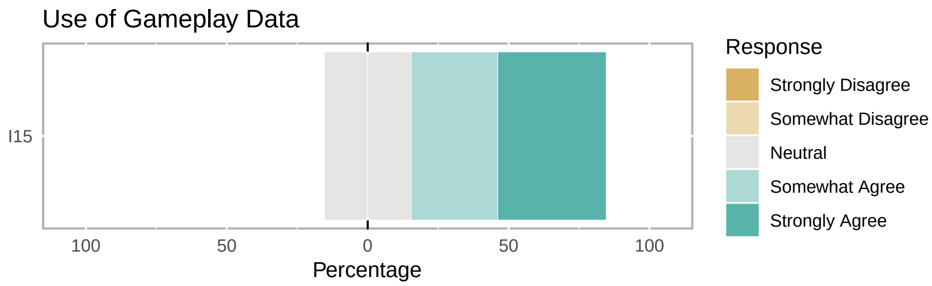


Figure 5.19: Responses to item I15 on Universal Design for Learning (N=13)

agreement (4.2) that it was a good idea to have a choice between completing assessments in a game or on paper. This is consistent with UDL checkpoint 7.1, which states that autonomy can be improved by offering choice in assessing skills.

Items I3 and I4 indicated agreement with the inclusion of alternative representations of traditional two-dimensional content in an immersive VR environment. This is consistent with UDL checkpoint 1.3, which is to offer alternatives for visual information. For example, the representation of graphs in VR, providing a means to interact (virtually touch) objects, and providing audio cues when key concepts have been learned improve the game from this perspective.

I5 had strong agreement that the game could help sustain enthusiasm for the subject. Sustaining enthusiasm overarches the multiple means of engagement checkpoints, particularly the *recruiting interest* and *sustaining effort and persistence* groups of UDL checkpoints.

I6 addressed the hands-on nature of VR and the ability in the game to move around and grab objects. There was quite strong agreement (4.4) that participants found it suited their way of learning. This was another way for the participants to express a preference for active (or kinaesthetic/tactile) learning over passive (introspective or contemplative) learning. This is consistent with the *physical action* checkpoints of the UDL framework.

I7 was a negative control question concerning the use of DGBL to teach graph theory. The participants disagreed that reading about graph theory was better than engaging in DGBL to learn about the subject. This is consistent with several UDL checkpoints, such as 2.5, which advocates illustrating through multiple media—in other words, accompanying traditional texts with DGBL (and various graphical representations of the material) is preferable to just the texts on their own.

I8 and I15 concerned metacognition and self-regulation through visualizations—or being given a tool to help gauge progress over time. There was agreement that the visualizations did help in this way. This is consistent with several UDL checkpoints, including 8.4, which concerns mastery-oriented feedback, the *self-regulation* group of checkpoints, and the *executive functions* checkpoints of goal-setting, planning and strategy management, and enhancing capacity for monitoring progress.

I9 and I10 addressed the final exercise in the game, which introduced a timed element and thus offered novelty and an increased level of challenge. The participants strongly agreed that this element positively challenged them. This is consistent with UDL checkpoint 8.2, which advocates varying demands to optimize challenge.

I11 asked participants whether participants found the two examples (the social graph and the natural language processing graph) relevant. They agreed that they were. This is consistent with UDL checkpoint 3.1, which advocates anchoring what is taught in prior knowledge, and 7.2, which suggests optimizing relevance. For example, the social graph example provides something that is relatable (people who purchase books from publishers) and explains how it relates to websites they are likely to have used, such as Amazon and Twitter.

I12 and I14 concerned the way instructions were broken down into chunks and progressed in terms of difficulty. Participants agreed that the instructions were step-by-step, and therefore easy to digest, and did not advance too quickly in difficulty. This is consistent with UDL checkpoint 3.3, which suggests that information should be "chunked" and released progressively.

I13 concerned the mastery of skills and participants agreed that the sequence of tasks allowed them to build mastery of the concepts. This related to several UDL checkpoints, including 3.3 (discussed in the previous paragraph), 8.4 (mastery-oriented feedback) and arguably the checkpoints related to transfer and generalization, self-regulation and executive functions—self-identifying as having become masters of the concepts should indicate that the participants were able to assess their progress and whether they were now able to apply the newly gained knowledge in the real world.

5.3.3.3.6 Age as a Factor

Item A2 asked participants how old they are. Ages were grouped into several groups: typical first-time undergraduate student ages of 18 to 24, then bands of 10 years (25 to 34, 35 to 44, 45 to 54 and 55 to 64), and those aged 65 and older.

Table 5.9: Age Profile of Participants

Age Group	N
18 to 24	11
25 to 34	2
35 to 44	1
45 to 54	5
55 to 64	1
65+	0

Because students were targeted as part of the recruitment process, there is a high proportion of participants in the 18 to 24 age group. The other participants were spread out among the age groups, with a cluster in the 45 to 54 age group. It was decided that to gain any statistical insight, it would be necessary to group all those of 25 years and older into a single group and compare younger participants with older participants (who might be considered of mature student status).

Group means were examined for a selection of the questionnaire items and these are listed in Table 5.10.

For many of the items, there is little difference in the means. There are, however, some notable, if not always statistically significant, variances that are worth exploring.

B1, which concerns improved understanding of graph theory, is significantly more positive for younger participants. Younger participants indicated they had a slightly higher level of pre-participation knowledge of graph theory (Table 5.12), but it seems unlikely this would have a major bearing on the variance between the age groups on improved understanding—in any event, item A7 is not very granular and there is only 1 choice in between *none* and *a lot*. The item asks participants to agree or disagree about their improvement in understanding. It is possible that despite starting with a slightly greater knowledge of graph theory, the game saw younger participants improve their understanding more than older participants.

Table 5.10: Selected Item Means by Age Group

Var.	Y.Mean (N=11)	Y.SD	O.Mean (N=9)	O.SD
B1	4.36	0.67	3.67	1.32
B2	4.55	0.65	4.00	0.78
C1	4.82	0.41	4.67	0.71
C2	4.27	0.67	4.44	0.88
D1	4.64	0.51	4.33	0.71
E1	4.27	0.47	3.89	1.27
E2	4.36	0.67	4.11	0.78
E3	4.45	0.69	4.11	0.78
F3	4.64	0.67	4.89	0.33
F6	4.45	0.69	3.78	1.39
F7	4.73	0.65	3.78	1.30
I1	4.45	0.69	4.56	0.73
I3	4.55	0.82	4.56	0.73
I4	4.36	0.81	3.67	1.32
I6	4.55	0.69	4.33	1.12
I7	4.55	0.69	3.78	1.39
I8	4.27	0.91	4.67	0.50
I9	4.73	0.47	4.44	1.01
I11	4.27	0.47	4.44	0.73
I12	4.09	0.94	4.67	0.50

Y = Younger Group (18-24), O = Older Group (25+)

B2, which concerns the relevance of what participants learned about graph theory, has a fairly significant variance with younger participants more positive about that aspect of the game. It is possible that there is a correlation between relevance and understanding—indeed, Table 5.11 suggests that it is.

Table 5.11: Correlation between improved understanding of graph theory and seeing its relevance

Correlation (B1, B2)
0.86

To determine the statistical significance of the observed differences (between the null hypothesis that age has no bearing and the hypothesis that it does), an independent t-test (Welch Two Sample) was run for those items with >0.5 Likert points between the two age groups (B1, B2, F6, F7, I4, I7, I12) to examine the difference in means between the two populations. A t-test is appropriate when there are two levels such as the two age groups.

Table 5.12: Self-reported pre-existing graph theory knowledge

Age Group	Mean	SD	N
18 to 24	1.73	0.647	11
25 +	1.56	0.527	9

1 = No previous knowledge

2 = Covered a little as part of prior studies

3 = Significant graph theory knowledge

Table 5.13: Independent t-test results for age groups

Var.	t	df	p-value
B1	1.435	11.351	0.178
B2	1.165	10.040	0.271
F6	1.330	11.146	0.210
F7	1.996	11.192	0.071
I4	1.383	12.694	0.190
I7	1.508	11.146	0.159
I12	-1.746	15.724	0.100

None of the variables reached the gold standard of <0.05 for the p-value (that is, moderate to strong evidence against the null hypothesis), however, F7 (being motivated to retry a challenge to gain a badge) and I12 (that the instructions were step-by-step and easy to digest) are approaching statistical significance (that is, there is weak evidence to suggest that the null hypothesis does not hold). F7 is particularly interesting given the evidence that gamers can become addicted to gaming—the World Health Organisation (WHO) has recently added *gaming disorder* as a recognised disease (WHO 2018) (Gray (2018) cautions against jumping to conclusions about whether someone is addicted to gaming)—and how achievement is one of the motivators behind gaming (Yee et al. 2012). There is perhaps the danger that players will be conditioned in the classic behaviourist way, or because of a mild addiction to the release of dopamine, to seek the reward in whatever form it presents, even for an exercise that loses some of its novelty after the first attempt.

5.3.3.3.7 Gender as a Factor

As outlined in Section 5.3.1.4, recruiting non-male participants proved to be difficult. As Table 5.14 shows, only 2 of the participants were non-male, both female and both non-students. While this makes any statistically significant findings impossible, it is unfortunate that the proportion of female students in computer science is very low. The most recent statistics published by the Higher Education Authority in Ireland shows that just 16% of ICT enrolments in third level were female (15% in Institutes of Technology).

Table 5.14: Gender of Participants

Gender	N
Male	18
Female	2
Other	0

Because of the very small number of female participants, it was deemed of no use to calculate any further statistics based solely on gender. The participation of female participants is also discussed in Section 5.3.3.1 where height was discovered as an issue for VR.

5.3.3.3.8 VR Experience as a Factor

A potentially important factor is experience with virtual reality. Participants were asked to provide their level of experience, with choices limited to no prior experience, some prior experience (less than 4 times), or frequently or own a VR headset. Table 5.15 shows the distribution among the three choices. There was an even split between no experience and some experience, with no one reporting ownership of a VR headset.

Table 5.15: VR Experience of Participants

Prior VR Experience	N
Never used VR	10
User VR up to 3 times	10
Frequently or Own VR	0

Several hypotheses could be imagined for some VR versus no VR experience. Those with prior experience will have had an opportunity to adjust to the novelty of VR and the types of controls used. It could be expected that those without VR experience would experience a greater frustration, taking longer to complete the tutorial level (which was the case—see Section 5.3.3.4.1), for example. However, there were no statistically significant differences in terms of enjoyment, motivation, mastery of the game's controls, or efficiency.

Table 5.16: Independent t-test results for no prior VR experience versus limited VR experience

Var.	t	df	p-value
C1	0.397	15.096	0.6967
C2	-0.268	17.990	0.792
D1	0.000	16.642	1.000
I1	0.6396	14.918	0.5321

5.3.3.3.9 Videogame Playing Frequency as a Factor

Participants were asked to indicate how often they played videogames on a days-per-year basis. Table 5.17 shows that frequency of gameplay was fairly polarised with 6 never playing videogames and 7 playing videogames at some point during the course of more than 100 days in a year. To get some meaningful results, the participants were split into two groups: *never to occasional* (those playing during the course of less than 1 month's worth of days) and *frequent* (those playing more often).

Table 5.17: Days During Which Videogames Were Played

Frequency (per year)	N
< 1	6
1 to 7	1
8 to 28	4
29 to 100	2
101+	7

A number of items that could be affected by frequency of videogame play were examined for statistical significance, particularly those related to motivation.

Table 5.18: Selected Item Means by Videogame Playing Frequency Group

Var.	R.Mean (N=11)	R.SD	F.Mean (N=9)	F.SD
C1	4.73	0.65	4.78	0.44
C2	4.27	0.91	4.44	0.73
D1	4.36	0.67	4.67	0.50
I1	4.64	0.67	4.67	0.71
I2	4.27	1.10	4.67	0.50

R = Rare to Occasional, F = Frequent

It is encouraging to see little difference between frequent and infrequent videogame players. A worry would be that non-videogame players would be less enthused about DGBL, but this is not the case according to these results. There are a small number of items where frequent videogame players are more positive about their agreement, such as the use of DGBL as part of their formal assessment, but none are statistically significant.

5.3.3.4 Triangulation of the Observation, Questionnaire and Gameplay Data

The observations allowed for behaviour to be observed, such as their engagement, strategies employed, how they fared from a usability point of view, and so on. The questionnaire mostly dealt with the perceptions of participants: how they enjoyed the game, how much they think it helped their understanding of graph theory, and so on. The captured gameplay data gives us the facts about their performance: how long was spent carrying out tutorial tasks, at what rate they progressed through the exercises, and so on. We can combine the three datasets and make some additional findings through triangulation, which can improve the accuracy and reliability of the data (Denscombe 2014). Figure 5.20 shows that in the centre, all three are combined for the highest level of confidence.

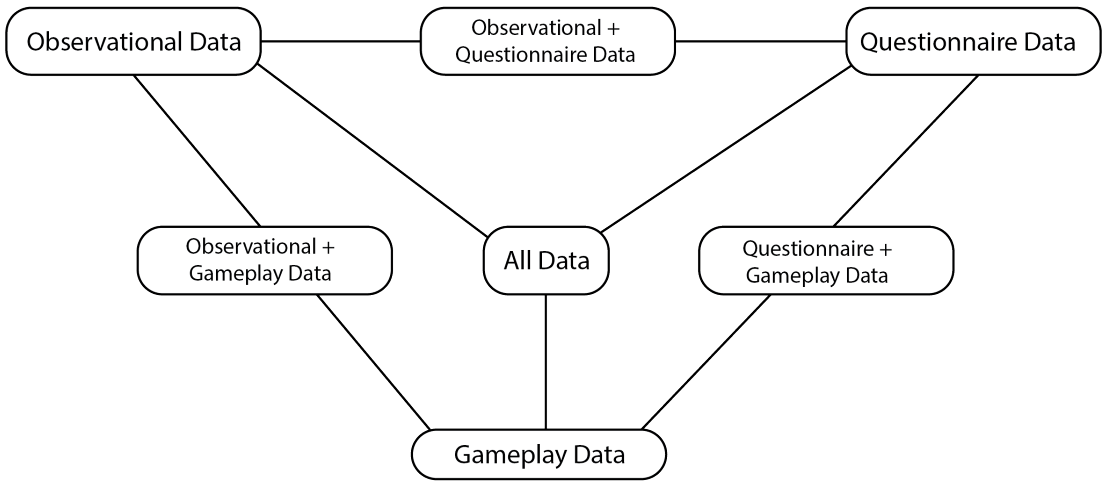


Figure 5.20: Triangulation of the three datasets

The following subsections show some of the ways in which the data can be triangulated to either garner additional insights or improve confidence levels in the findings. The sections are not meant to be exhaustive, instead showing the potential for mixed methods research to lead to more or better quality insights.

5.3.3.4.1 Triangulating Questionnaire and Gameplay Data

Table 5.19: Gameplay Metrics: Means by Age Group

Variable	Y.Mean (N=10)	Y.SD	O.Mean (N=9)	O.SD
Tutorial Tasks Duration	319 sec	148 sec	416 sec	155 sec
Exercise 1 Duration	253 sec	222 sec	254 sec	144 sec
Exercise 2 Duration	332 sec	173 sec	417 sec	128 sec
Exercise 3 Duration	322 sec	122 sec	238 sec	93.6 sec
Total Exercises Duration	907 sec	356 sec	909 sec	275 sec
Total Examples Duration	309 sec	145 sec	433 sec	102 sec

Y = Younger Group (18-24), O = Older Group (25+)

It took older participants (aged 25+, or what would be classified as mature student age) significantly longer to complete the tutorial tasks (see Table 5.19). The t-test yielded a p-value of 0.183 (see Table 5.20), meaning the difference is not statistically significant for this study sample. However, it was evident from the observational part of the study that older participants were less familiar with game controllers and struggled a bit with getting used to holding them.

While total exercise durations was almost identical (907 seconds versus 909 seconds), there was a difference between exercises 2 and 3. Exercise 2 involved connecting related species; rats, mice, rodents and mammals are likely to be well known to all participants. However, exercise 3 involved synonyms and phrases and it is possible that performance in this type of exercise could correlate with experience—having spent more years building up a vocabulary. The t-test yielded a p-value of 0.109, which is just short of weak evidence of statistical significance. It would likely take more exercises of different types with a larger sample to make definitive conclusions.

Table 5.20: Independent t-test results for age groups (gameplay data)

Var.	t	df	p-value
Tutorial Tasks Duration	-1.389	16.595	0.183
Exercise 1 Duration	-0.012	15.575	0.991
Exercise 2 Duration	-1.223	16.445	0.239
Exercise 3 Duration	1.694	16.632	0.109
Exercises Duration	-0.014	16.660	0.990
Examples Duration	-2.179	16.167	0.044
Examples Engagement	-0.606	9.997	0.558

Where there was a statistically significant variance was in time spent with the real-world examples (p=0.044). Does this mean that older participants were more engaged with them? It is probably unwise to draw that conclusion from just durations alone. The engagements metric was added for iterations 2 and 3 of the study. With participant H's data not stored, this left just 12 participants, only 4 of which were under 25 (see Table 5.21). On average, the older participants had 4.5 more interactions (teleports and vertex grabs), but the small sample size for participants under 25 means it is not statistically significant (p=0.558).

Table 5.21: Examples Engagements: Means by Age Group

Variable	Y.Mean (N=4)	Y.SD	O.Mean (N=8)	O.SD
Examples Engagements	13.5	8.02	18.0	17.70

Y = Younger Group (18-24), O = Older Group (25+)

Table 5.22: Independent t-test results for prior versus no prior VR experience (gameplay data)

Var.	t	df	p-value
Tutorial Tasks Duration	1.6595	14.379	0.119
Exercises Duration	1.0068	16.391	0.3286
Examples Duration	1.8003	16.313	0.090

With respect to prior VR experience (see Table 5.22), the extra time taken by participants with no prior VR experience, 425.8 seconds, compared to prior VR experience, 310.9 seconds, was not statistically significant (0.119), but is worth noting. It suggests that those without any prior VR experience struggled more to get to grips with the game's mechanics. On the other hand, time spent with the exercises had weak significance (0.09) in terms of those without prior VR experience taking more time to go through the examples.

5.3.3.4.2 Triangulating Observational and Gameplay Data

A number of usability issues were encountered during the analysis of observational notes in Section 5.3.3.1.2. Section 5.3.3.2.6 discussed the findings from the gameplay data from a usability perspective. The grab mechanic, in particular, had a wide distribution with outliers, meaning that some participants quickly mastered the mechanic, but a significant number of participants took time to master the mechanics (see Figure 5.12). It was also clear from Figure 5.11 that there were a number of spikes in duration for the grab mechanic. Returning the analysis of the observation notes, “depth perception issue” was a code associated with several participants in relation to their attempts to grab a vertex for the first time. This is an example of a case where a visualization of gameplay data identifies a potential issue with usability (grabbing) and the observational notes offer a contributing factor. It is then possible to try to resolve the issue (for example by examining the background, lighting, shadows, and so on).

The observational data also revealed occasional frustration and resorting to trial and error to complete an exercise. This corresponds with the discussion of individual exercise performance in Section 5.3.3.2.4 where participant T was noted as having a particularly noisy incorrect connections line; an observational note was recorded that the participant had engaged in a “lot of trial and error”. The same participant was not a native English speaker (as noted in Section 5.3.3.1.5). This is another example of triangulation identifying that there is an issue and offering a potential cause of the issue. A solution can then be implemented, such as internationalizing challenges based on language (something that would improve the game from a UDL perspective).

5.3.3.4.3 Triangulating Observational and Questionnaire Data

It was also possible to refer to the findings of the questionnaire analysis to see why some participants had more significant issues using the controls than others. According to section 5.3.3.3.9 11 of the 20 participants were infrequent players (playing video games during 28 days or less per annum), with 6 of those never playing video games. These participants are less familiar with controllers and button layouts.

An additional triangulation between questionnaire and observational findings concerns immediate feedback. Some participants verbalised their confusion about whether they were supposed to carry out an exercise (on a real world example) or if they had reached the end of an exercise. This could explain why immediate feedback scored slightly lower than cumulative feedback (discussed in Section 5.3.3.3.2).

5.3.3.4.4 Triangulating All Three

The previous three sub-sections showed the use of two datasets to corroborate certain findings or to use one finding to explain another. This section shows how all three datasets can be used together. For many findings this is not possible. For example, enjoyment or novelty cannot be determined from gameplay data. However, it is possible to look at three distinct pieces of data and use them to improve confidence in a finding.

The questionnaire asks participants how much they agree with the following statement:

> I think I can see applications of graph theory in the real world / industry having participated in the game based learning activities.

The gameplay data captures engagement statistics, as discussed in Section 5.3.3.2.2. The analysis of observational notes produced the theme of engagement. A reasonable hypothesis is that a higher level of engagement with a real world example will lead to a greater appreciation of its relevance through reflection (assumed if the participant spends more time interacting with the example), backed up by theories such as Kolb's experiential learning cycle (Kolb 2014).

5.3.4 Discussion of the Learner Study

5.3.4.1 Summary of Findings

Because of the mixed methods approach employed, the learner study is a complex one to summarise. The methodology behind the study proved to be suitable for both formative and summative evaluation. The following is a summary of the main findings and these will be mapped in the next section to the research questions:

F1 With the iterative approach employed (three iterations with 7, 7 and 6 participants respectively), it was possible to identify many usability issues and to resolve them between iterations. Issues fell into two categories: those that could be prevented by orientation of learners prior to playing, and issues that can only be fixed by updating the game itself. A longer orientation in iterations 2 and 3 reduced the number of preventable issues and other issues were fixed by updating the game's code.

F2 Some issues of usability remain to be resolved, including catering for internationalization of text and catering for those of a short stature.

F3 Learners employed a range of strategies to solve the exercises.

F4 The game was immersive and novel, with occasional frustrations that affected the game's balance.

F5 It was possible to measure the level of learner engagement with a wide range of engagement found.

F6 The instructional materials were relevant and for the most part guided the learner well, but there were occasional issues of instructional quality that led to confusion as to the next step.

F7 The game supported many approaches to learning, including being methodical, thinking out loud, and practising until a level of comfort was reached. In addition, several learning preferences were supported, including visual and hands-on learners.

F8 The data captured during gameplay allowed for a range of visualizations that revealed a range of metrics, including overall gameplay durations, engagement and exercise performance (including comparative performance).

F9 The data captured also allowed visualization of the mastery of the game's mechanics. It was possible to identify that the grab mechanic was problematic for several participants.

F10 The game was successful in terms of its effectiveness (learning outcomes, motivation and efficiency).

F11 The game was successful in terms of its feedback.

F12 The game's gamification mechanics (badges and a leaderboard) were successful in terms of motivation and self-regulation.

F13 Participants were happy for their data to be used by educators to measure their progress and performance.

F14 The use of VR technology did not cause any significant issues, with issues related to ill-fitting HMDs and glitches due to sensors causing minor discomfort or distraction.

F15 The game and platform (including dashboard) was successful from a

UDL perspective, giving the participants choice of learning and assessment medium, suiting their learning preferences, making the subject matter interesting and relevant, helping them gauge their progress, delivering instructions to them and bringing them through the instructional materials step by step (or in easy-to-digest chunks), thus allowing them master the concepts presented.

Furthermore, it was shown that triangulation of results could add new insights or increase confidence levels in existing findings.

5.3.4.2 How the Findings Contribute to Answering the Research Questions

Table 5.23 maps the findings of the previous section to the research questions. Based on the mapping of the findings to the research questions, it seems clear that they contribute significantly to answering yes to each of the questions. It was now up to the practitioners of the second study to agree or disagree.

Table 5.23: Mapping of Findings to Research Questions.

Research Question	How the Findings Support the Research Question
RQ1: Will the AMDGBL allow for iterative improvement of the graph game prototype?	F1 indicates that having three iterations improved the game each time from a usability perspective. Key metrics were gathered for formative and summative evaluation that could enable the game to be improved in terms of engagement and balance (F8) and it was possible to identify problematic game mechanics (F9). Many of the other findings could be reviewed as part of a formative evaluation between iterations to identify if the game was falling short of its goals in terms of engagement, effectiveness, and so on. F14 was useful to iron out any issues related to the VR hardware setup.
RQ2: Will the use of the AMDGBL lead to an effective DGBL solution?	F10 explicitly supports the effectiveness of the solution from the perspective of learning outcomes, motivation and efficiency. However, the game was effective in other ways, including supporting many approaches or preferences to learning (F7), being immersive and novel (F4), being successful in terms of feedback (F11), being successful from a gamification (and therefore extrinsic motivation) point of view (F12), being successful in terms of effectiveness of instruction (F15), and relevance of instructional materials (F6). However, F6 does also show that there were some issues with the instructional materials in terms of the learners being unsure about a next step.
RQ3: Will the inclusion of UDL in the model lead to a game that is more universally designed?	F15 summarizes the success of the game and platform from a UDL perspective (in terms of learner choice, learning preferences, relevance, self-regulation, step-by-step and progressive instruction, allowing for mastery of the concepts). F1 also points to an improved game from a UDL perspective, with many usability issues resolved in each iteration. F2 does point, however, to more work to do in this area, but the ability to identify issues means that ultimately the game will continue to be improved from a UDL perspective. Other findings point to the success of the game and platform from a UDL perspective, including learner autonomy (F3), relevance (F6), learner preference (F7), self-regulation and executive functions (F8 and F12) and immediacy of feedback (F11).
RQ4: Will a learning analytics dashboard help learners with executive functions?	F8 shows that learners were provided with the means to assess their performance and progression and F11 shows that they receive immediate and summative feedback on their performance. F15 captured how successful the platform was in allowing learners to gauge their performance.
RQ5: Will the immersive and open nature of the VR environment foster learner autonomy?	It is clear from the range of strategies employed in solving the exercises (F3) that the game supports learner autonomy and open inquiry (both discussed in Section 2.5.4). Learner autonomy involves learners taking responsibility for their learning, as does open inquiry, and without guidance as to a recommended strategy many of the participants discovered strategies that helped them more quickly solve the exercises. The strategies can be classified at the highest level of Simpson's psychomotor domain, discussed in Section 2.4.2.1, which would classify the creation of such new movements as *origination*. In that respect, the game can also be said to be successful from a psychomotor or kinaesthetic perspective. A contributing factor was the immersive nature of the environment (F4) and the ability to engage widely with the real world examples (F5).

5.4 The Practitioner Study

5.4.1 Overview

While the first study examined how learners interacted with the game and platform, the second study examined what game-based learning practitioners thought about the approach used in the design and development of the game and the platform. The reason for doing the studies in that order was to:

1. allow the first study produce learning analytics for the practitioners to consider and reflect upon;
2. have a case study demonstrating the methodology in action for the practitioners to consider and reflect upon.

The following sections describe the case study construction, the methodology employed, the results of the study and a discussion of the results.

5.4.2 Case Study Construction

Cohen et al. (2017, p.375-376) provide many definitions from the literature of what a case study is. They tend to have boundaries and the unit can be at the level of the individual, group, organization, community, or nation. Cohen et al. clearly state that the researcher must explain what the unit of the case study is. In the case of the learner study, this is a group of study participants representing a typical laboratory group of twenty students. They also state that researchers should be specific about the boundaries of the case and the level of analysis carried out. A case study, they write, "provides a unique example of real people in real situations, enabling readers to understand ideas more clearly than simply by presenting them with abstract theories or principles".

Case studies in education, according to Bassey (1999), and summarised here by Cohen et al. (2017, p.376), can be:

> conducted in order to inform decision making by policy makers, practitioners and theorists. They investigate 'interesting aspects of an educational activity, programme, or institution, or system mainly in its natural context and within an ethic of respect for persons' such that plausible, trustworthy explanations and interpretations can be offered

> after collecting sufficient data in exploring the 'significant features of the case' (p. 58).

The learner study is, obviously, an education case study (of 20 students/study participants engaging in an educational activity—playing a learning game and viewing learning visualizations) and was intended to be presented to practitioners for their consideration. Interesting or significant aspects were selected from the learner study outputs so that a case could be constructed. Figure 5.21 provides a diagram of how the case was constructed—once interpretation had been completed, the interesting or significant features of the case were selected (such as the evidence of trial and error, the identification of issues with mechanics, and the different strategies employed, all discussed in section 5.3.4).

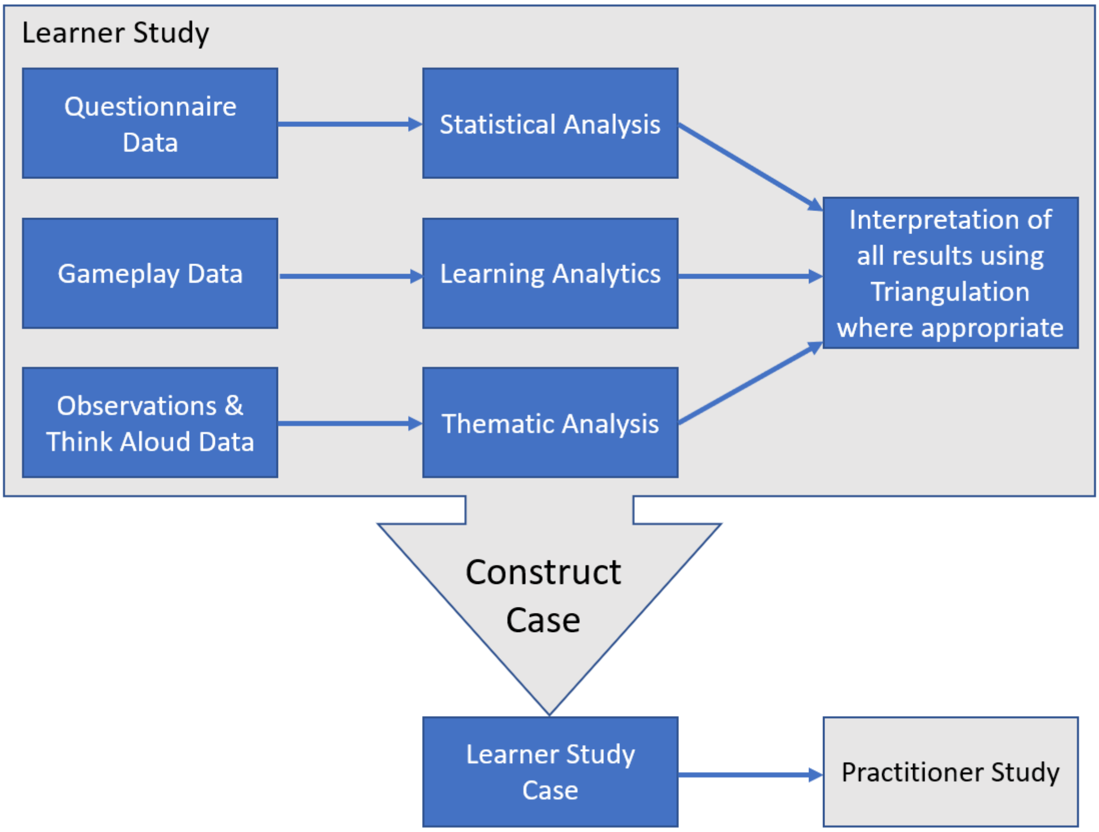


Figure 5.21: Construction of the learner study case study.

The case study was presented to the practitioners in three ways (these methods are discussed in more detail in the next section):

1. During either a video or live presentation, the nature of the learner study was explained and selected anecdotes (such as observations made or comments spoken by the participants), findings from an analysis of the data (including, and particularly, triangulation), and visualizations were discussed.
2. The video contained a complete playthrough of the game to demonstrate a slice of a "real situation" as it would have happened as the learners (or study participants) engaged in the game-based learning activity. On the other hand, some practitioners (the six local ones) were able to play the game for themselves.
3. Some of the open questions in the questionnaire (see Appendix B.1) referenced visualizations produced during the learner study.

It should be noted that while much of the literature on case studies writes about the "writing up" of a report, the case study in this research was presented largely in oral and visual form through either the medium of video, or during a live presentation. A hyperlink to the video is available in Appendix B.3.

5.4.3 Methodology

5.4.3.1 Overview

The first study included a questionnaire with primarily closed, Likert-scale questions for a number of reasons, including the fact that observational notes already added a qualitative element to the study, and the fact that the participants had already engaged in a lengthy and cognitively-heavy activity when playing the game and examining the visualizations, thus making open questions either unfair or unproductive as participants become either tired or impatient. Bryman (2008, p.232) points to the greater effort required by respondents and how this can lead to lower participation rates.

The second study was less cognitively taxing, requiring participants to watch a demonstration of gameplay followed by an explanation of visualizations. In other words, it was more passive than the first study. This meant that asking the participants to complete a questionnaire featuring open-ended questions was more plausible than it would have been for the first study. Bryman (2008) does point to a significant disadvantage of using self-completion questionnaires featuring open questions in that they typically have low response rates. Therefore, it was important that participants were appealed to on the basis that the study being carried out was relevant to them and that they were contributing to their own field of research—in other words, they had a vested interest in seeing the research succeed. The field of game-based learning research is an emerging and still relatively small one, so it was important that given the relatively small population of practitioners, that response rates were high.

An additional disadvantage listed by Bryman is the effort required of the researcher to code the responses. Another disadvantage listed that is not relevant to this study, because of the single researcher involved and the use of an online questionnaire, is the lack of consistency when more than one researcher records answers.

The advantages of open questions include participants being able to answer on their own terms, unusual or unexpected answers can emerge, and an accepted range of answers is not suggested to the participants, thus getting a truer reflection of their own thoughts and opinions (Bryman 2008, p.232). Open questions are also more appropriate than closed ones when the respondents' thoughts and feelings need to be analysed in more depth (Dohrenwend 1965), as was the intention with the second study.

Because of the open responses to the questions in the survey, a qualitative approach was used to examine the text for meaning—specifically, a thematic analysis was carried out using the same methodology as the analysis of observational notes in Section 5.3.3.1, and in particular the analysis of the pedagogical notes.

Again, Graneheim and Lundman (2004) was referred to for the procedure of the thematic analysis. The text was scanned for *meaning units*, which were *condensed* and then *coded*. These codes were then grouped under *categories*, which in turn were grouped under *themes*. The broad themes allowed for a high-level discussion of the findings, while categories, codes and meaning units could still be examined for further context.

The following sub-sections go into more detail about the questions posed, how the participants were identified (and how many) and how the survey was administered.

5.4.3.2 Study Design

An online self-completion questionnaire was chosen as the medium for gathering responses. Online surveys also have several advantages over paper-based surveys in terms of cost, speed, easier access to a larger population, convenience (respondents can choose when to complete them), accuracy and exportability of data (for example to a spreadsheet) (Cohen et al. 2017). There are some disadvantages, according to Cohen et al., such as abandonment and the possibility the email with the hyperlink will be treated as spam—some other disadvantages listed are not a factor, such as lack of internet expertise (DGBL practitioners are almost certain to be highly-proficient users of technology).

In comparison to face-to-face interviews, one significant drawback of a questionnaire compared to an interview is the inability to probe for more information or ask follow-up questions (Bryman 2008, Cohen et al. 2017), which means that the design of the questions is very important (Bryman 2008)—they should be clear and unambiguous.

Questions were devised that would ask the practitioners about the important aspects of the game, the platform and the model. The following eight areas were identified for questioning based on how they justify the research carried out and contribute to answering the research questions:

1. The effectiveness of DGBL—if the practitioners consider DGBL to be ineffective, it raises a question about the need for the game, platform and model in the first place.
2. The use of VR—a clear hypothesis was developed concerning the benefit of VR in terms of learner autonomy in particular, but there are other potential benefits to VR identified in the literature, as discussed in Section 2.4.
3. Learning analytics dashboards—central to the model is the use of LADs and the hypothesis that they will help learners to perform executive functions, such as goal setting and planning.
4. Mapping learning to a taxonomy to clearly visualize learning progression.
5. The agile, iterative approach with frequent prototyping involving key stakeholders.

6. The use of analytics for formative evaluation during development.
7. The embedding of the UDL framework in the model.
8. The mixed methods approach and triangulation of data to gain new insights or improve confidence in findings.

Appendix B.1 shows the question text for the eight areas (see questions 3 to 10 in the survey). Two additional questions were added: the first asked for a name to confirm consent and the second asked for a description of the respondent's duties and optionally a job title. The latter was intended to give some context to the responses. It should be noted that when referencing Q1 in the survey, this refers to question 3 in Appendix B.1, Q2 refers to question 4, and so on up to Q8 referring to question 10 in the online survey.

There were several outputs from the first study that could be used in the second study. For example, the gameplay data allowed for visualizations to be produced for individual or cumulative exercise performance, engagement and the identification of usability issues. In addition, findings from an analysis of the observational notes and questionnaire responses (and triangulation of gameplay, observational and questionnaire data) meant that a summary of the findings from the study could be discussed with DGBL practitioners. This allowed for three additions to the practitioner study:

1. While the gameplay demonstration proceeded, the researcher was able to discuss findings, such as the strategies employed while solving exercises.
2. When the demonstration of gameplay was complete, a number of visualizations were shown and explained. Several of these (particularly those generated using R) were generated as a result of the data analysis carried out in the learner study.
3. Some of the questions had a supporting image to jog the respondent's memory in relation to the prior demonstration of the visualizations and give further context to the questions (see questions 4, 5, 6 and 8).

A wired Oculus Rift VR set-up is not very portable. There are multiple sensors, a HMD, a heavy PC case, monitor and other various peripherals and cables. It also requires careful calibration with alignment of sensors and demarcation of play area. Therefore, it is not practical to go on a tour of many locations to physically reach the greatest number of participants. Instead, it was decided to set up in two locations (Cork Institute of Technology and University College, Cork) and to bring local participants to those locations. Other participants would take part remotely by watching a video prior to completing a survey.

The researcher played through the full game, recording every action using a video capture tool called *Action!*[5]. This was approximately 12 minutes in length. Screenshots were then taken of each page of the web-based dashboard, along with a selection of the charts generated using R (see Section 5.3.3.2). The gameplay recording and the screenshots were imported into an *Adobe Premier*[6] project. Audio commentary was recorded using *Adobe Audition*[7] and a *Blue Yeti*[8] microphone to ensure a noise-free recording. Each file was then edited and combined and exported to a 23-minute MP4 video file, which was then uploaded to YouTube.

5.4.3.3 Ethical Considerations

There was a discussion of ethics in general terms in Section 5.3.1.3. These considerations were carried forward into the second study, which was carried out in accordance with the researcher's employer's *Code of Good Practice in Research* (Cork Institute of Technology 2014), which states that "[h]onesty, integrity, openness, accountability and fairness should inform all research practice." According to the document, only ethical issues which cannot be decided upon with reference to the document alone should be referred to CIT's Research Ethics Committee (REC). In particular, it states that "respect will be accorded to [participants] in terms of their rights, dignity, self-worth and psychological and physical harm."

5.4.3.4 Recruitment of Participants

Typically, qualitative researchers use purposive (or non-probability) sampling as opposed to probability sampling (Bryman 2008, p.375,414). Purposive sampling is "strategic" with the aim of recruiting participants that are relevant to the research questions being asked (Bryman 2008, p.415).

Determining a sample size for qualitative research is not as easy to determine as it is for quantitative approaches and probability sampling. It tends to rely

[5] https://mirillis.com/en/products/action.html
[6] https://www.adobe.com/ie/products/premiere.html
[7] https://www.adobe.com/ie/products/audition.html
[8] https://www.bluedesigns.com/products/yeti/

more on rule of thumb, with the number of groups in the sample being a determining factor (Bryman 2008, p.462). For example, if it was deemed important to compare male versus female practitioners, a larger sample size would be needed. However, the sample for this study consists of a single group, which is DGBL practitioners with a significant knowledge of the development of DGBL solutions. No distinction is being made on the grounds of age, geography, experience with particular technologies, and so on.

One approach to determining a sufficient sample size is saturation. Saturation can be used as a criterion for researchers to decide when research should discontinue, and it has its origins in grounded theory (Saunders et al. 2018). Bryman (2008, p.462) cites the example of a study (Guest et al. 2006) that despite having 60 interview transcripts, found that saturation was reached when around 12 transcripts had been thematically analysed—after 6 transcripts were coded 73% of all codes had been discovered, with 92% after 12, and the remaining codes occurring sporadically thereafter; that is to say, just 20% of the transcripts produced 92% of the codes. Some caveats are noted, such as the homogeneous nature of the study participants and the narrowness of the questions. Guest et al. (2006) highlight an issue with saturation, which is that you cannot determine prior to data gathering when saturation will be reached.

Boddy (2016), having extensively reviewed the literature on qualitative research sample sizes, found that for a homogeneous group (which, arguably, the DGBL practitioners are) 10 may be enough and anything above 30 is unwieldy. Based on this and the Guest et al. (2006) study, a sample size of 12 was chosen. The data would then be analysed to ensure a high degree of saturation had been reached and determine if more participants were required (which ultimately were not required).

The sample for the second study was not a convenience sample. While some of the participants were local and therefore convenient for local participation, they were nonetheless game-based learning practitioners and relevant to the research questions. The aim was to gather a sample that was representative of the wider population of game-based learning practitioners, which meant selecting candidate participants on the basis of several characteristics and with a degree of judgement on the part of the researcher as to their suitability (as discussed in Cohen et al. 2017, p.217).

To be considered a candidate participant, the practitioner needed to have one or more of the following characteristics:

- The person has published a paper related to game-based learning;
- The person works as an educational technologist and has a knowledge of the current state-of-the-art in game-based learning;
- The person works as a consultant in the private sector developing game-based learning solutions.

Several web-based searches were performed to identify candidates, such as:

- Searching Google with search terms such as “Game Based Learning Researcher” and “Serious Games Researcher”;
- Searching Google for local game-based learning activity with search terms such as “GBL Cork”;
- Getting a list of institutes of technology and universities in Ireland and searching Google more specifically by including the name of the institution;
- Going directly to the web-sites of Irish higher education institutes to search for their technology-enhanced learning (TEL) departments or game-based learning research groups.
- Searching LinkedIn for people with job titles that included TEL-related words like “learning” and “training”;
- Identifying game-based learning research papers and extracting the authors and their institutions in order to identify contact details.

For each candidate identified, their profiles were examined, such as their publication history or descriptions of their current research activity. Where it was clear they were actively-engaged game-based learning practitioners, they were approached via email to ask if they would participate in the study. Each email sent was personalized—see Appendix B.2 for a sample email. For example, if the candidate listed learning analytics as a current research interest, the email included text to the effect that the researcher shared a common research interest and that the study might be of interest for that reason.

Candidates were identified throughout Ireland and beyond. This included:

- Lecturers, researchers and TEL specialists in Irish institutes of technology and universities;
- Lecturers and Researchers in a number of UK universities;
- Consultants working on private sector contracts.

In total, 40 were identified as candidates and all were emailed. 2 emails bounced, leaving 38 who it can be assumed received the email. Of those, 10 were invited to attend a local demonstration and 28 to view the online video remotely. Of the emailed candidates, 16 responded that they would take part (8 local and 8 remote). In the end, as planned, 12 completed the survey (6 local and 6 remote). Local candidates were invited to attend, in-person, a demonstration of the VR learning game and learning analytics dashboard. Remote participants (those outside Cork) were invited to take part in the study via online means by watching a recorded video of gameplay and the learning analytics dashboard with commentary by the researcher.

To ensure the video provided as much information as an in-person demonstration, an event was held in UCC with a number of staff involved in technology-enhanced learning invited. The gameplay and visualizations were demonstrated and questions were asked and answered. In addition, three local participants (each of whom completed the online survey) were invited on an individual basis to attend a demonstration of the platform in Cork Institute of Technology. Only after all of this was the video recorded and the researcher's audio commentary addressed questions asked during the previous in-person demonstrations. This gave a high degree of confidence that remote participants were equally as well informed as in-person participants.

The profiles provided by the respondents can be found in Table E.5. It should be noted that three of the participants were known to the researcher because of occasional interactions with them in the researcher's place of employment, but they did not work in the same department. A pragmatic decision was taken to recruit these participants due to the relatively small population of GBL practitioners and the difficulty in recruiting enough participants.

5.4.4 Findings

5.4.4.1 Overview

A similar approach to thematic analysis as was covered in Section 5.3.3.1 was carried out. The benefits and issues associated with thematic analysis were covered in that section. For the practitioner study, the online survey responses were copied into an Excel spreadsheet for coding. This began with highlighting meaning units. Figure 5.22 shows a snippet from the response data with highlighting (using different colours to make them stand out).

Digital games are an effective means of teaching a variety of skills and knowledge - whether they are educational, "serious" games or not. For instance, recreational games can teach various soft skills and motor skills without having been designed specifically to educate. Digital games are a good means of reinforcing learning as a complement to traditional teaching practices.	Providing an immersive environment where the user can learn risk free, without fear of consequences. Can be more cost effective to provide certain scenarios through VR. Allows for active learning and exploration - can help to keep the user engaged and interested.
"Digital game-based learning" cannot be taken as being effective or not! Yes, there is a huge amount of research showing effective examples of it, but I've experienced plenty that don't work too (not mentioned so much, publication bias etc). So I would say that WELL-DESIGNED digital game-based learning can be incredibly effective and motivating. However it depends on the learning design, mechanic design, narrative design (if any), and environment/scenario design much more than it depends on something being digital or a game.	Spatialisation, definitely, used well in your prototype. Intuitive for some people. Provides focus as user disembodied from real world. Disadvantages should be balanced against this of course and they are many: IO barrier (e.g. your grab mechanic), disorientation/dizziness, accessibility, expense, health and safety, disembodiment, social isolation etc.

Figure 5.22: An example of how meaning units were highlighted in the Excel spreadsheet (effectiveness of DGBL on the left and benefits of VR on the right).

Where meaning units were part of a list, the full sentence involving the meaning unit was reconstructed. For example, in response to the benefits of VR, one respondent provided a list of disadvantages to counter the benefits:

> Disadvantages should be balanced against this of course and they are many: IO barrier (e.g. your grab mechanic), disorientation/dizziness, accessibility, expense, health and safety, disembodiment, social isolation etc.

This one sentence yielded eight meaning units:

1. Disadvantages should be balanced against this of course and they are many;
2. A disadvantage of VR is the IO barrier (e.g. your grab mechanic);
3. A disadvantage of VR is disorientation/dizziness;
4. A disadvantage of VR is accessibility;
5. A disadvantage of VR is expense;
6. A disadvantage of VR is health and safety;
7. A disadvantage of VR is disembodiment;
8. A disadvantage of VR is social isolation.

Each question was coded separately rather than all answers to all questions as a single group. For each question, the meaning units were condensed and then categorised before themes emerged.

5.4.4.2 Q1 - Effectiveness of DGBL

40 meaning units were extracted from the responses to Q1. These were first condensed and then 44 codes were identified. The 44 codes were organized into 16 categories (Table 5.24). These produced 5 themes (Table 5.25).

Table 5.24: Categorization of codes for Q1

Category	Codes			
Conceptual Integration	Must be well integrated (x2)			
Complementary	Use alongside traditional	Not a replacement	Reinforces learning alongside traditional	
Effective Design	Design for specific LOs	Integrated curriculum	Motivating done well	Effective done well
	Learning design important	Mechanic design important	Narrative design important	Siutation/context important
	Non-digital or game elements important too			
Engagement	Hook interest	Engages (x3)	Fun	Felt experience
Motivation	Extrinsically motivates	Motivating done well	Effective done well	
Learning	Great pedagogical effect	Improved learning transfer	Variety of learning	Immersion improves learning
Situated / Contextual	Situated learning	Situation/context important		
Transformative Effect	Transformative effect			
Cognitive Benefits	Knowledge retention	Learning transfer		
Disadvantages	Expensive	Time-consuming	Not suited to all	Not always effective (x2)
	Non-positive not publicised		Expensive when focus is narrow	
Extra Benefits	Digital literacy	Collaboration		
Use of DGBL	Under-utilized			
Non-DGBL Games	Learning in entertainment games			
Practitioner Skills	Practitioners often lack right mix of skills	Practitioners lacking game dev knowledge produce games lacking fun	Practitioners lacking pedagogical knowledge produce ineffective games	
Lack of uptake	Uptake Effected Because Unproven		Uptake Effected Because of Scepticism	
Accessibility	Not suited to all			

Table 5.25: Themes for Q1

Theme	Categories		
Importance of Good Design	Effective Design	Conceptual Integration	Accessibility
Positive Effect on Engagement	Engagement	Motivation	
Pedagogical Benefits	Learning	Cognitive Benefits	Transformative Effect
	Collaboration	Digital Literacy	
Embedding in Curriculum	Complementary	Under-utilized	Non-DGBL Games
Lack of Uptake	Lack of Uptake	Disadvantages	

The following findings emerged from the thematic analysis of responses to Q1:

Q1.F1 DGBL is effective from a learning, engagement and motivational perspective when designed well.

Q1.F2 This requires the integration of several aspects of good game design, such as effective mechanics and narrative, along with pedagogical aspects, such as well-designed learning for specific objectives, and the integration of the wider curriculum into a game.

Q1.F3 This can lead to cognitive benefits such as improved knowledge retention and learning transfer.

Q1.F4 However, DGBL developers must be equipped with the right skills and experience (which they often lack), otherwise the resulting game could be either ineffective or lacking fun.

Q1.F5 It facilitates situated learning where the relevance of learning can be highlighted.

Q1.F6 One respondent went as far as to say that DGBL can have a lasting transformative effect on the learner.

Q1.F7 The benefits can extend beyond the game's content with improvements to digital literacy and team work (so called "soft skills").

Q1.F8 Another respondent pointed to the learning potential of non-DGBL games, such as ones designed primarily for entertainment, in terms of motor and soft skills.

Q1.F9 DGBL is under-utilized and can be complementary to traditional teaching and learning methods, though according to one respondent should not be a replacement for traditional methods (“face to face and contact time”).

Q1.F10 There are, though, several disadvantages to DGBL that affect its uptake by educators: because it must be well-designed and proven to be effective, it follows that there are examples of ineffective DGBL (which does not often get highlighted in the literature on DGBL effectiveness); it can be expensive and time-consuming to develop. There is also a healthy scepticism about DGBL on the part of educators that affects adoption.

5.4.4.3 Q2 - Benefits of VR

41 meaning units were extracted from the responses to Q2. These were first condensed and then 42 codes were identified. The 42 codes were organized into 8 categories (Table 5.26). These produced 4 themes (Table 5.27).

Table 5.26: Categorization of codes for Q2

Category	Codes			
Engagement	Engaging (x3)	Fun	Novelty	Must be entertaining
	Cognitive wow factor			
Future R&D	Unexplored	Huge potential	Make more use of VR	Very exciting
	Need to figure out what works in VR			
Usability	Ease of use	I/O issues	Intuitive	
Accessibility	Distance learning	Accessibility issues	I/O issues	Dizziness
	Representation issues	Assessment issues		
Specific Skills	Soft skills	Psychomotor skills	STEM	
Realism and Relevance	Realistic (x2)	Authentic experiences	Augments	Amplifies
	Immersive (x2)	Intuitive manipulation		
Pedagogical Benefits	Risk free	Social	Active learning	
	Exploration	Focus	Spatialisation	Distance learning
	Affordance of VR may support certain learning			
Disadvantages	Expensive	Take disadvantages into account	I/O issues	Accessibility issues
	Dizziness	Social isolation	Health and Safety	Assessment issues
	Representation issues			

Table 5.27: Themes for Q2

Theme	Categories		
Learning Affordances	Pedagogical Benefits	Realism and Relevance	Specific Skills
Unexplored Potential	Future R&D		
Universal Design Challenges	Usability	Accessibility	
Disadvantages	Disadvantages		

The following findings emerged from the thematic analysis of responses to Q2:

Q2.F1 VR provides many significant learning affordances.

Q2.F2 It is highly engaging and has a wow factor that makes the platform novel.

Q2.F3 The immersive nature of the medium enables the possibility of realism and therefore increases relevance of the material.

Q2.F4 The medium, with its intuitive manipulation of 3D objects, for example, allows for the involvement and development of psychomotor skills and it can develop other specific skills such as soft skills and is particularly useful for STEM subjects.

Q2.F5 Among the other pedagogical benefits are the level of focus afforded by a disembodiment from the real world (and its distractions), the active nature of some of the learning, how it supports exploration, the risk free nature of a virtual environment, and the sense of space (and being in it) that it gives.

Q2.F6 VR is challenging from a usability standpoint: it can be intuitive and easy to use (when natural movement is allowed), but introduces input / output issues, for example depth perception issues.

Q2.F7 From a universal design point of view, it supports access and choice, for example by allowing learning to occur at a distance, but is not accessible to all—for example, it can cause dizziness.

Q2.F8 There are other disadvantages to the medium that need to be taken into account; for example, it is expensive, can be socially isolating (when not used in a collaborative way), and has health and safety concerns.

Q2.F9 There is huge, as-yet-unexplored and exciting potential in the medium: more use needs to be made of VR, but it will take time to figure out what works best in VR.

5.4.4.4 Q3 - Benefits of Learning Analytics Dashboards

42 meaning units were extracted from the responses to Q3. These were first condensed and then 36 codes were identified. The 36 codes were organized into 7 categories (Table 5.28). These produced 4 themes (Table 5.29).

The following findings emerged from the thematic analysis of responses to Q3:

Q3.F1 Learning analytics dashboards (LADs) help learners, through personalized visualizations and other information, with metacognition and to be more autonomous. This includes executive functions, such as goal setting and gauging progress. It also allows for peer comparison, though there was a dissenting response that questioned whether peer comparisons would lead to an unhealthy competitiveness in the classroom.

Q3.F2 LADs are becoming increasingly important to researchers and educators, not just because they are of benefit as a diagnostic tool in terms of identifying struggling students and intervening to help them, or because of their motivational affordance, but also because it is a growing trend and it cannot be ignored by DGBL practitioners.

Q3.F3 LADs require careful design. When implemented they can often be under-utilized and there may be several reasons for this: educators may struggle to interpret the visualizations and learners may struggle in how to interpret the data they are presented with.

Q3.F4 To counter this, educators need to be provided with guidance on how to use the LAD and visualizations need to be simplified for learners, such as simple traffic light indicators; where possible, the information should be presented to the learner as close to the learning context as possible; the information presented to both learners and educators needs to be concise and actionable.

Table 5.28: Categorization of codes for Q3

Category	**Codes**			
Metacognition	Self-assessment	Goal setting	Feedback on progress	Essential for evaluation
	Reflective	Identify actionale items	Self-direction	Show students where they are weak
	Peer comparison	No peer comparison		
Autonomy	Autonomy	Self-direction		
Motivation	Motivating	Badges motivate		
Design Considerations	Under-used	Educator needs guidance (x3)	Learners may struggle with LAD	Simplify for learners
	Concise data	Actionable (x4)	Viz must add new info	Keep close to learning context
	Simple prompts to stium-late reflection			
Importance	Big trend	Great for researcher	Don't know	Beneficial (x2)
Identify	Identify strugglers	Intervention	Identify trends	Identify balance issues
	Identify usability issues			
Personal	Personalized	Adpative		

Table 5.29: Themes for Q3

Theme	Categories		
Autonomy	Autonomy	Metacognition	Personal
Importance	Importance	Motivation	
Careful Design	Design Considerations		
Diagnostic	Identify		

5.4.4.5 Q4 - Learning Progression Data and Visualization

22 meaning units were extracted from the responses to Q4. These were first condensed and then 22 codes were identified. The 22 codes were organized into 6 categories (Table 5.30). These produced 4 themes (Table 5.31).

The following findings emerged from the thematic analysis of responses to Q4:

Q4.F1 Visualizing learner progression supports learner executive functions, such as assessing performance, progress and setting goals for work to do. Some learners may struggle to interpret "complexity", so an alternative, such as "time required" might be considered.

Q4.F2 It supports the evaluation of a game's design formatively and summatively.

Q4.F3 It has the potential to support cutting edge features, such as predictive analytics (e.g. future performance), trends, the automation of learner supports and real-time feedack to the learner during gameplay.

Q4.F4 However, there are considerations when implementing this approach, such as educating the instructor in its use, setting up all of the learning outcomes and mapping them to learner interactions in the game, and allowing the instructor to customize other aspects, such as a choice of taxonomy. Additionally, the use of an industry standard, such as xAPI, for the API should be considered.

Q4.F5 While seen as largely of benefit (in terms of usefulness, interest from the perspective of DGBL designers, and motivation), one respondent noted that not all instructors will agree with the linear approach of taxonomies like SOLO and Bloom's and the metaphor of linear learning paths.

Table 5.30: Categorization of codes for Q4

Category	Codes			
Executive Functions	Visualize progress	Visualize work to do	Visualize performance	
Implementation Considerations	Educator needs guidance	Linear approach may not suit all	Set up	Customization
	Consider industry standard [API]			
Evaluation	Formative evaluation	Summative evaluation	Contextualisation	
Analytics	Identify problem areas	Trends		
Advanced Functions	Prediction	Automation	Realt-time feedback	
Benefits	Useful for educator	Interesting	Motivating	Completion graph good
	Complexity usefulness unclear	API good		

Table 5.31: Themes for Q4

Theme	Categories		
Executive Functions	Executive Functions		
Cutting Edge Features	Advanced Functions	Benefits	Analytics
Design Evaluation	Evaluation		
Implementation Considerations	Implementation Considerations		

5.4.4.6 Q5 - Iterative / Agile Approach

27 meaning units were extracted from the responses to Q5. These were first condensed and then 28 codes were identified. The 28 codes were organized into 6 categories (Table 5.32). These produced 4 themes (Table 5.33).

The following findings emerged from the thematic analysis of responses to Q5:

Q5.F1 The design and development of DGBL should be process-oriented, with an emphasis on continuous improvement and evaluating progress towards intended goals.

Q5.F2 The iterative process proposed can handle the complexity of DGBL, is more efficient and allows practitioners understand the process, assess progress and share feedback.

Q5.F3 Iteration helps everyone better understand the requirements, which can help to manage expectations.

Q5.F4 There is an inevitable move from traditional ADDIE-style development to modern iterative and agile processes in DGBL and it is becoming (or maybe has already become) best practice, and this is only following the lead of other industries, such as the video games industry and other design-focused industries.

Q5.F5 An iterative DGBL design and development process should be inclusive of all stakeholders, particularly learners, who can help DGBL developers arrive at the best solution.

Q5.F6 However, there are some drawbacks, such as the extra cost, the possible need for ethical approval, and the limited availability of stakeholders, particularly at certain times of the academic calendar.

Table 5.32: Categorization of codes for Q5

Category	**Codes**			
Game Industry Testing	Game Industry Testing (x2)			
Evaluation	Identifies issues	Evaluate intended learning		
Necessity	Only way to go	Iterations necessary	Way things are going	Used elsewhere
	Preferred approach	Common practice	Traditional to Modern	Experience with it
Process	Handles complexity	Efficient (x2)	Understand process	Understand progress
	Manage expectations	Share feedback		
Continuous Improvement	Refines experiential learning	Improves playability and transfer	Improves design	
Inclusion	Include stakeholders (x2)	May not be feasible to include stakeholders	Include learners	Include expert learners
Drawbacks	More expensive	Ethical approval	Limited availability of stakeholders	Academic year

Table 5.33: Themes for Q5

Theme	**Categories**		
Process Oriented	Process	Continuous Improvement	Evaluation
Best Practice	Game Industry Testing	Necessity	
Inclusive	Inclusion		
Drawbacks	Drawbacks		

5.4.4.7 Q6 - Use of Visualizations for Formative Evaluation

22 meaning units were extracted from the responses to Q6. These were first condensed and then 25 codes were identified. The 25 codes were organized into 6 categories (Table 5.34). These produced 3 themes (Table 5.35).

The following findings emerged from the thematic analysis of responses to Q6:

Q6.F1 The use of visualizations to identify issues (such as usability, balance and flow) and determine effectiveness allows for continuous improvement of a DGBL solution.

Q6.F2 The visualizations are a diagnostic tool that can provide specificity in identifying issues, providing actionable issues to further diagnose and resolve—however, while it can pinpoint issues efficiently, particularly for large numbers of users, it cannot in itself provide an answer as to how the issue should be resolved.

Q6.F3 The use of visualizations like this might not be common in DGBL, but they have been used to diagnose user experience issues with other types of software and therefore it may be best practice to make use of them in DGBL.

Table 5.34: Categorization of codes for Q6

Category	Codes			
Identify	Identify issues (x4)	Quantitative		
Diagnosis	Specificity	Actionable	Does not diagnose	Not most important diagnostic tool
	Cannot diagnose in isolation			
Speed	Efficient (x2)	More efficient that qualitative when larger number of users	Shorten feedback loop	
Evaluation	Determine effectiveness	Evaluate technology		
Improvement	Improve flow	Improve skill development		
Best Practice	Used for other software types	A good development		

Table 5.35: Themes for Q6

Theme	Categories	
Continuous Improvement	Improvement	Evaluation
Diagnosis	Diagnosis	Identify
Best Practice	Best Practice	Speed

5.4.4.8 Q7 - Embedding UDL in the AMDGBL

17 meaning units were extracted from the responses to Q7. These were first condensed and then 13 codes were identified. The 13 codes were organized into 7 categories (Table 5.36). These produced 4 themes (Table 5.37).

The following findings emerged from the thematic analysis of responses to Q7:

Q7.F1 What is clear is that while there is a general awareness that universal design is either a good practice or best practice, there is limited knowledge about universal design (UD) among the respondents, and no specific knowledge about the UDL framework.

Q7.F2 There is an acknowledgement that UD creates universality from the perspective of accessibility, designing for all learners and autonomy; however, it was noted that trying to design for all is either difficult or almost impossible.

Q7.F3 There was agreement that it made sense to embed UD at the heart of a model for DGBL and that an established, scrutinized framework should be chosen—that it is not simply something tacked on to cater for "special needs".

Table 5.36: Categorization of codes for Q7

Category	Codes		
Best Practice	Good practice (x3)	Established	Scrutinized
Good idea	Good idea (x3)		
Accessibility	Good for accessibility	Facilitate users	Some technologies not accessible to all
Design for all	Design for all (x3)	Difficult to design for all (x2)	
Embed in Model	Good model (x3)	Alternative UD frameworks	
Awareness	Do not know much about it (x3)		
Autonomy	Flexibility to increase autonomy		

Table 5.37: Themes for Q7

Theme	Categories		
Best Practice	Best Practice	Good idea	
Universality	Accessibility	Design for all	Autonomy
Embed in Model	Embed in Model	Alternative UD frameworks	
Awareness	Awareness		

5.4.4.9 Q8 - Triangulation

14 meaning units were extracted from the responses to Q7. These were first condensed and then 12 codes were identified. The 12 codes were organized into 4 categories (Table 5.38). These produced 4 themes (Table 5.39).

The following findings emerged from the thematic analysis of responses to Q8:

Q8.F1 Using both quantitative and qualitative methods in a complementary way can be the ideal approach so that the weaknesses of one method can be compensated for by another.

Q8.F2 Triangulation, which was identified as a strong feature of the research, can be used to identify more serious issues that would introduce unnecessary challenge and ultimately prevent the learner from continuing with a game.

Q8.F3 The opportunity to automate using quantitative methods (analytics) can streamline evaluation.

Q8.F4 However, there are some challenges, particularly the additional expertise required; qualitative methods can be relatively quick and easy to set up at little expense compared to learning analytics, which would require some expertise of data analytics or statistical analysis, for example.

Q8.F5 The approach can shift from usability focus in earlier iteration to learning focus in later iterations.

Table 5.38: Categorization of codes for Q8

Category	**Codes**			
Complementary	Quantitative complements qualitative (x6)	Ideal		
Identify	Ensure correct challenge	Identify serious issues	From usability to learning in future iterations	
Challenges	More expertise required	More expensive	Qualitative methods easier	Qualitative methods quicker
	Qualitative methods less expensive			
Automation	Automation (x2)			

Table 5.39: Themes for Q8

Theme	**Categories**
Complementary Methods	Complementary
Identify Challenging Issues	Identify
Disadvantages	Disadvantages
Automation	Automation

5.4.5 Discussion of the Practitioner Study

5.4.5.1 Summary of Findings

The following is a summary of the findings from the eight questions in the practitioner study. The findings are summarised by question.

Q1 DGBL is effective in terms of learning, engagement and motivation, but it must be designed well to integrate game and pedagogical components. DGBL is under-utilized and can complement traditional methods of teaching and learning, though not usually as a direct replacement. However, it has not always been successful (which is a reason for ensuring good design practices) and can be expensive and time-consuming to develop.

Q2 VR is an exciting medium that is as yet largely unexplored in a learning context. It has many positive pedagogical benefits, including a high level of engagement and novelty, the use and development of psychomotor skills, and support for different learning preferences, including the visual or active learner. Its immersiveness and realism can increase the relevance of what is presented. It provides a risk free environment that supports exploration. It can increase focus. It can improve learner choice. However, there are disadvantages such as cost and inaccessibility to some.

Q3 Learning analytics dashboards help learners to be more autonomous and helps with executive functions such as goal setting and planning. They are of increasing importance to educators because they can identify learners in need of intervention. LADs require careful design because they can end up being under-utilized and educators will need to be educated on how to interpret the visualizations presented—the information presented needs to be concise and actionable. They need to be simple enough for the great majority of students, so metaphors like traffic lights can help comprehension.

Q4 The mapping and visualization of learner progression can support learners' executive functions, such as assessing performance and progress, and setting goals for work to do. It can support formative and summative evaluation. It can support cutting edge features, such as predicting learner performance and this can be automated because of the learner interaction data.

Q5 The iterative / agile approach of the AMDGBL is process-oriented with an emphasis on continuous improvement of the DGBL solution under development. The iterative process allows for complex solutions to be developed. It is an inclusive process that ensures all stakeholders understand requirements and are kept up to date on progress. The move to iterative and agile methods is well under way and is only following the lead of other industries.

Q6 Using visualizations as part of formative evaluation can identify issues of usability, flow and balance, as well as measuring effectiveness. Issues can be diagnosed, but further analysis is required to provide a solution to the issues. The approach can be seen as best practice and is only catching up on similar approaches to the evaluation of other software.

Q7 DGBL practitioners agree that universal design is important and should be embedded (rather than just added on at the end) in any model or framework for DGBL development. Practitioners are aware of the benefits (and challenges of providing them), such as improved accessibility and learner autonomy. However, it is clear that the specifics of universal design and in particular the UDL framework are largely unknown to many practitioners.

Q8 Employing a mixed methods approach is seen as best practice, though it is noted that the inclusion of quantitative methods based on gameplay data alongside qualitative methods requires more expertise and adds more expense. Through triangulation, it is possible to identify more complex issues. Evaluation could be streamlined with the automation of analytics.

5.4.5.2 How the Findings Contribute to Answering the Research Questions

Table 5.40 maps the findings of the previous sections to the research questions. Based on the mapping, it seems clear that they contribute significantly to answering yes to each of the questions.

Table 5.40: Mapping of Findings to Research Questions.

Research Question	How the Findings Support the Research Question
RQ1: Will the AMDGBL allow for iterative improvement of the graph game prototype?	The findings from Q5, in particular, point to the benefits of continuous improvement through iteration. This stems from the process-oriented nature of the AMDGBL. The ability to handle complexity, and to continuously evaluate progress due the continuous feedback the model allows, all improve what is delivered.
RQ2: Will the use of the AMDGBL lead to an effective DGBL solution?	The findings from Q1 indicate that DGBL is effective when designed well and integrates game and pedagogic components. The AMDGBL includes the integration of learning (outcomes, context, theory, and so on) as well as game elements (for example the MDA framework) by mapping learning outcomes to learner interaction events. Some of the findings from Q4, Q5, Q6 and Q8 point to continuous improvement as part of an iterative, agile process and how this can identify issues, such as usability and balance, so that the game delivered has the best chance of being effective.
RQ3: Will the inclusion of UDL in the model lead to a game that is more universally designed?	The findings from Q7 point to the benefits of embedding UDL at the heart of a model from DGBL development, though the more generic term of *universal design* was better understood and is therefore a proxy for the inclusion of the lesser-known UDL framework in the model. The benefits identified, such as improved accessibility and autonomy are explicitly addressed by the UDL framework.
RQ4: Will a learning analytics dashboard help learners with executive functions?	The findings from Q3 and Q4 support the assertion that a LAD will support executive functions, such as goal setting and planning, as long as they are carefully designed so that learners can easily interpret visualizations.
RQ5: Will the immersive and open nature of the VR environment foster learner autonomy?	The findings from Q2 show that VR offers a high level of engagement and novelty, can allow learners employ and develop psychomotor skills and will suit active, visual or hands-on learners. These findings, and also the finding that it can be a risk free environment (compared to the real world) with spatialisation that supports exploration, support the assertion that VR fosters autonomy.

5.5 Chapter Conclusion

This chapter detailed two studies that were undertaken using a pragmatist paradigm. The first was a study of how learners interacted with the graph game and used a mixed methods approach that included qualitative (observations and think aloud) and quantitative (questionnaire with closed questions and gameplay data analytics) methods. The learner study section discussed the design of the study, ethical consideration and the recruitment of participants. Using this approach, twenty participants were selected using a primarily purposive sampling approach to represent a typical cohort of learners that would study undergraduate and postgraduate computer science courses. Following the research protocol, the participants signed a consent form, were oriented in the use of VR and then began playing the game. As the players played, observational notes were taken and the players encouraged to verbalise their thoughts. When gameplay was complete, the participants were shown visualizations of their learning. The participants then filled in a questionnaire of primarily five-point Likert scale questions. The data (observational notes, questionnaire and gameplay) were analysed using multiple techniques: thematic analysis for the observational notes, means, medians and standard deviation for the Likert responses, and the gameplay data was visualized to identify usability issues and to look for patterns in exercise performance. In addition, Welch t-tests were performed to compare groups and triangulation of data was performed. Fifteen core findings were made (such as the variety of strategies employed by learners when solving challenges, how it was possible to identify usability issues using data, how the game was perceived to be effective from a learning, motivation and efficiency perspective, and how the game and platform provided learners with feedback) and these were mapped to the research questions. The findings supported answering ‘yes’ to each of the research questions.

The chapter then continued into the practitioner study. A purposive sample of twelve DGBL practitioners either participated in-person in a demonstration of the VR game or remotely watched video of gameplay with commentary by the researcher. They were also shown visualizations that would be available to learners and / or educators. This provided context for the online questionnaire that followed. Open questions asked about the effectiveness of DGBL and VR, the benefits of learning analytics dashboards, the mapping of learning to a taxonomy to visualize learning paths, the use of an agile, iterative approach to

DGBL design and development, formative evaluation and how it can identify issues through analysis of gameplay data, embedding the UDL framework at the heart of the AMDGBL, and the use of multiple methods to triangulate data to improve confidence or gain new insights. A thematic analysis was performed on the response textual data. Numerous findings were made under each question and these were summarised. The findings were then mapped to the research questions and they contributed to answering 'yes' to each of them. The practitioner responses positively supported the approach of the AMDGBL and highlighted the importance of designing DGBL solutions effectively to integrate learning with gameplay, which is what the AMDGBL was designed to do.

Chapter 6

Conclusion

6.1 Thesis Summary

Chapter 1 began with the motivation for and the background to the research carried out for this thesis. It set out the research questions to be answered and the research objectives to be completed to answer them.

Chapter 2 surveyed the state of the art in several areas related to the research questions and objectives, including play and games, digital game-based learning and how it can be designed for effectiveness and integration of learning and gameplay, virtual reality, theories of teaching and learning and models of instructional design, agile software development, universal design, and the use of data for learning analytics and AI.

Chapter 3 set out the structure and the processes of the AMDGBL. The diagram highlighted the iterative and agile nature of the model and how formative evaluation is at its heart. The phases of the model were detailed: the analysis and design, build, study, formative evaluation, delivery and summative evaluation phases.

Using the AMDGBL approach, Chapter 4 provided a detailed, step-by-step account of how the AMDGBL platform and the VR-based graph game were designed, implemented and evaluated. It showed how learning and gameplay can be integrated: learning outcomes were devised using the SOLO taxonomy, the game mechanics were structured according to the MDA framework, and then the LM-GM model was used to ensure the two were integrated according to the pedagogical considerations set out. The game was comprehensively formatively evaluated from several perspectives to provide confidence that the game would be motivational, support focus and flow while being in balance, would facilitate the intended type of learning, and support a wide range of autonomous and empowered learners.

Chapter 5 detailed two studies that were undertaken. The first was a study of how learners interacted with the graph game and used a mixed methods approach that included qualitative (observations and think aloud) and quantitative (questionnaire with closed questions and gameplay data analytics) methods. The data (observational notes, questionnaire and gameplay) were analysed using multiple techniques: thematic analysis for the observational notes, means, medians and standard deviation for the Likert responses, and the gameplay data was visualized to identify usability issues and to look for patterns in exercise performance. The findings included the variety of strategies employed by learners when solving challenges, how it was possible to identify usability issues using data, how the game was perceived to be effective from a learning, motivation and efficiency perspective, and how the game and platform provided learners with feedback, and these were mapped to the research questions. The findings supported answering yes to each of the research questions.

Chapter 5 then continued into the practitioner study. A qualitative approach was taken with open questions that asked about the effectiveness of DGBL and VR, and the respondents thoughts about including the various components / processes of the AMDGBL, and the use of multiple methods to triangulate data to improve confidence or gain new insights. A thematic analysis was performed on the response textual data. The practitioner study positively supported the approach of the AMDGBL and highlighted the importance of designing DGBL solutions effectively to integrate learning with gameplay, which is what the AMDGBL was designed to do.

6.2 Research Questions and Objectives

This section discusses whether the research questions and objectives outlined in Chapter 1 have been met, beginning with the research objectives that needed to be completed before the research questions could be fully answered.

6.2.1 Meeting the Research Objectives

O1 - Investigate ways in which DGBL solutions can be evaluated so that as each iteration produces a prototype, the prototype can be formatively evaluated in a timely manner to allow for improvement of the prototype during the next iteration.

The literature review identified several ways in which DGBL prototypes can be formatively evaluated using accessible and efficient models, lenses and frameworks, including universality, SGMs, balance, flow, motivation, and narrative.

O2 - Design and develop a learning analytics platform incorporating an API and web-based dashboard.

A learning analytics platform incorporating an API and web-based dashboard was developed and used during the learner study to create several different visualizations. The visualizations were shown to DGBL practitioners in the practitioner study.

O3 - Design and develop an effective, universally-designed VR-based DGBL solution using the AMDGBL.

A VR-based game that teaches the fundamentals of graph theory was designed using the analysis and design phase of the AMDGBL and developed using agile software development processes on the Unreal Engine 4 game engine. The learner study showed it was perceived to be effective and universally-designed.

O4 - Evaluate how well O2 contributed to the successful completion of O3 and also helped learners to perform executive functions.

The iterative approach to the learner study allowed data to be visualized. It was possible to identify problematic game mechanics and to improve them, for example by increasing the length of the trace line for the gaze mechanic to reduce vertex selection issues. It was also possible to identify patterns in the exercise performance data to see where trial and error had been employed—no action was taken to improve the game to reduce trial and error, but it has been noted for future work. Learners responded positively to statements about learner autonomy, learning progression, comparison to peers, badges and leaderboards.

O5 - Evaluate the opinions of DGBL practitioners on the AMDGBL approach to *the development of effective learning games.*

A study was carried out to get the opinions of DGBL practitioners on the core components of the AMDGBL model. A thematic analysis was carried out on their responses.

With the objectives met, it was possible to answer the research questions.

6.2.2 Answering the Research Questions

Both the learner and the practitioner studies concluded with a mapping of findings to the research questions. Each of the questions is presented here with a brief summary of findings from both studies.

RQ1 - Will the AMDGBL allow for iterative improvement of the graph game prototype?

The learner study found that multiple iterations improved the game each time in terms of usability. It was possible to identify levels of engagement, balance and problematic game mechanics, all of which point to specific areas to improve in future iterations. The practitioner study found that practitioners believe in the benefits of an iterative approach that delivers continuous improvement. This allows higher levels of complexity to be managed through continuous evaluation and shared feedback. The triangulation of findings from multiple methods was noted to be of significant value. The combination of findings from both studies supports the assertion that the iterative nature of the AMDGBL improved the graph game prototype.

RQ2 - Will the use of the AMDGBL lead to an effective DGBL solution?

The learner study found that the game was perceived to be effective from many perspectives, including learning outcomes, motivation, efficiency, immersion, novelty, feedback and relevance. Only minor issues, such as occasional confusion with instructions were found. The practitioner study found that DGBL practitioners believe that while there are some good examples of DGBL, there are many bad ones, and this is largely down to a lack of integration of learning and gameplay, which the AMDGBL purposely has at the centre of its analysis and design phase. The practitioner views support the use of iteration and formative evaluation to identify issues of balance and usability so that the game has the best chance of being effective. The combination of findings from both studies supports the assertion that the AMDGBL will improve the chances of developing an effective DGBL solution, though it cannot be guaranteed.

RQ3 - Will the inclusion of UDL in the model lead to a game that is more universally designed?

The learner study found that the game was successful from a UDL perspective in terms of learner choice, learning preferences, relevance, self-regulation, step-by-step and progressive instruction and allowing for mastery of the concepts. There were some issues that affected a small number of participants, such as those whose first language is not English or were short in stature, that remain to be resolved. However, other issues were resolved, such as mirroring controls for those who identify as dyslexic. The practitioner study found that while the UDL framework was not well known to the DGBL community, the general principles of UD were and it was acknowledged that this could improve accessibility and autonomy (which are at the core of the UDL framework). The combination of findings from both studies supports the inclusion of UDL at the heart of the AMDGBL.

RQ4 - Will a learning analytics dashboard help learners with executive functions, such as assessing their performance, setting goals and planning?

The learner study found that learners were able to assess their performance and progression and they received immediate and summative feedback on their performance. The practitioner study found that DGBL practitioners believe that LADs can support executive functions, but they need to be carefully designed to be easily understood and actionable. The combination of findings from both studies supports the assertion that a LAD will help learners with executive functions.

RQ5 - Will the immersive and open nature of the VR environment foster learner autonomy?

The learner study found that a range of strategies were employed by learners in the immersive VR environment, supported by locomotion and other kinaesthetic / tactile mechanics, such as grabbing vertices. This was supported by the level of immersion reported and engagement levels visualized. The practitioner study found that DGBL practitioners believe that VR offers a high level of engagement and novelty, that it can support psychomotor skills, and will suit learners who prefer active, visual or hands-on (kinaesthetic / tactile) learning. It was also noted that VR can be a risk free environment in which learners can experiment without consequences due to factors such as spatialisation. The combination of findings from both studies strongly points to VR fostering learner autonomy.

Because the research objectives were met, it was possible to answer all of the research questions. The answers to them were positive and support the need for the AMDGBL and the ability of the AMDGBL to deliver effective DGBL solutions that integrate learning and engaging gameplay. The inclusion of learning analytics and universal design at the heart of the AMDGBL was endorsed. The choice of VR as the medium for the game also proved successful from a learner autonomy standpoint.

6.3 Limitations

The learner study had some limitations. The main purpose of the study was to provide a case study to add context for practitioners in a second study (for example, providing examples of visualizations based on learner interaction data). The iterative approach taken meant that the first cohort of participants (N=7) played a slightly different version of the game to the second cohort (N=7), who in turn played a slightly different version of the game to the final cohort (N=6). The changes are marginal, being small improvements to usability or making some of the instructions clearer. This means that aggregating the findings, as was done when analysing the data from the multiple methods, comes with that minor caveat. However, the position of the researcher is that the changes are minor and did not change the core mechanics nor did they change the in-game challenges the learners faced. If they did have an effect on the data, it was negligible. It was also necessary to take this approach to demonstrate a level of continuous improvement through iteration. Getting all participants to play the same exact version of the game would have made improvement based on an analysis of gameplay impossible. The study also lacked balance in terms of gender. Attempts were made to recruit a representative number of females, but few responded to the recruitment email and of those that did only two turned up. Gender balance is a significant issue in computer science, as discussed earlier. The practitioner study fared better in terms of gender balance with five of twelve being female.

An additional limitation of the learner study was that it focused on *perceived* effectiveness rather than *actual* effectiveness. A more empirical approach is detailed by Cohen et al. (2017, p.405-7), such as a true or quasi-experimental study with pre- and post-tests, or even two groups learning simultaneously through traditional means (e.g. lecture) and the graph game (similar to an approach taken in All 2017, which found that a pre-test influenced the evaluation of effectiveness). This would have necessitated a larger sample size to ensure statistical significance. Had the focus of this thesis been on the game rather than the AMDGBL, this might have been a problem. However, the game was a case study for how to design and develop a DGBL solution using the AMDGBL. The study did support the assertion (if not definitively prove it) that the game was effective and provided discussion points for practitioners to consider in the second study. It is also a pragmatic approach, considering the lack of time and money often available for DGBL (a finding from the practitioner study).

As a demonstration of the AMDGBL in action, the approach to the design and development of the graph game had some shortcomings. The AMDGBL recommends involving stakeholders as soon as possible, ideally when a design is available, but certainly when the first functional prototype is completed. Stakeholder involvement did not occur until the prototype had been significantly developed by the researcher. Earlier input from learners could have produced a better game and provided a better case study for the second study. However, the three iterations performed were representative of iterations that might occur mid-project and there were improvements made between iterations.

The practitioner study asked DGBL practitioners to assess the approach of (or processes involved in) the AMDGBL. This was done after the practitioners had viewed or participated in a demonstration of the game and viewed visualisations. This could be considered a view from the outside rather than the inside, which would have involved practitioners designing and developing solutions using the AMDGBL. While this sounds ideal, it is highly impractical given the time it would take to develop even a simple DGBL solution. Therefore, the approach taken (asking the practitioners to first consider a case study of the AMDGBL in action) seemed the best possible approach.

The practitioner study treats the practitioners as a homogeneous group, ‘DGBL practitioners’. All of the respondents showed a good knowledge of DGBL and had at a minimum researched the subject to identify its potential in their line of work, with some of the participants defining their roles around DGBL. When it came to LA or UDL, knowledge was more mixed, but most were able to bring to bear their pedagogical knowledge when answering questions related to those topics. The researcher takes the position that the respondents were closely grouped in terms of their characteristics and knowledge and thus should be considered a homogeneous group. Table E.5 can be consulted to make a judgement on this, but it cannot be viewed in isolation of the thousands of other words (far too numerous to embed in this thesis) provided as answers to the questions that give a fuller picture.

An alternative approach to the inclusion of practitioners would have been to include them as stakeholders during the formative evaluation. Each of the three iterations of the prototype relied on learners to provide the data that would yield improvements to the next version of the prototype. Practitioners would likely have provided additional insights, such as improving the design of the LAD to be more actionable and understandable for learners.

6.4 Future Work

A number of possibilities for future work are discussed here. Some of the suggestions have emerged from experimentation, such as the replay feature, and others from the studies, such as the need to make the game more accessible.

- AI and ML were discussed at a high level in Section 2.8.2. Natural language processing combined with machine learning could be employed as the basis of an artificially-intelligent guide, providing advice and encouragement that sounds human. It was relatively easy for the human eye to see trial and error being employed in the exercise performance visualizations. It stands to reason that with labelling of this data as being ‘trial and error’ that a ML algorithm could detect such behaviour in real time and through NLP offer advice, hints or encouragement that sounds natural. This would make the game truly *adaptive* and future work could investigate ways of including real-time adaptive learning as part of the AMDGBL.
- The inclusion of every connection made between vertices, along with a

timestamp, means it would be possible to replay in real time a learner's challenge attempt, or even pause, rewind, and so on, similar to a video player. This facility was prototyped in the graph game (see Figure 6.1), but not pursued as far as including it in the learner study. This type of feature could be further enhanced by tracking bodily movement, including body location, hand positions and head position (including pitch, roll and yaw). This would be a significant increase in data and would require optimization of interaction with the API, but it would allow true fidelity in terms of playing back what a learner did (literally through the learner's eyes). While this may not be hugely useful in terms of the graph game challenges, it would be very useful in other scenarios—one could imagine a surgery, flight or boiler maintenance training simulator gathering this tracking data and allowing trainers replay trainee efforts in the company of the trainee and, like the cognitive apprenticeship model, discussing improvements.

- The game currently lacks a narrative, which can have a motivational effect on learning. Future work would involve designing a narrative structure into which a story, characters, setting, and so on, could be placed.
- The current version of the web-based dashboard provides visualizations to learners. Future work would include adding educator visualizations. The dashboard is a functional prototype, but it needs substantial additional work to make it more flexible, such as generalizing its approach to the visualization of exercise performance.
- Automation of alerts could be added so that when learners are not meeting their learning objectives, or struggle with exercises (such as resorting to trial and error), an email alert is sent or a notification displayed in the educator's dashboard to identify where intervention is required.
- One of the findings from the practitioner study was that information should be presented in an understandable way. A suggestion was a traffic light metaphor, providing red, green or amber indicators to highlight where progress is good or not so good.
- A number of findings from a formative evaluation of the game using the UDL framework in Section 4.5 highlighted a number of issues to resolve.

An example would be the porting of the VR game to a standard desktop or web player to increase availability (and by extension choice) and provide an alternative for players who are prone to VIMS. Another is allowing for the game to be customized to take into account the participant's height.

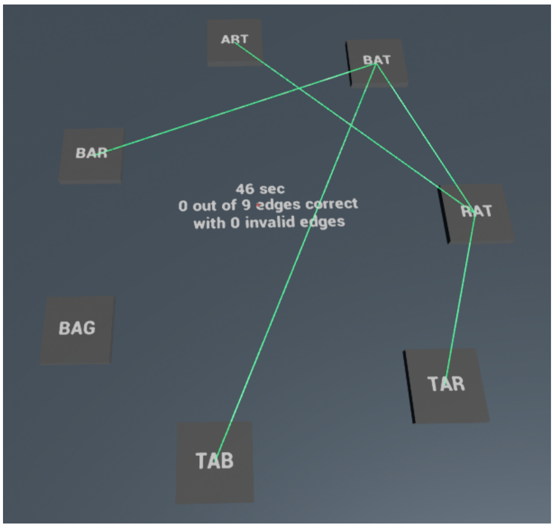


Figure 6.1: Functional early prototype of challenge replay feature.

Appendix A

The Learner Study Documents

A.1 Ethics Approval

Gmail **Larkin Cunningham <larkin.cunningham@gmail.com>**

Log 2017-133 - Approved minor comments

Ethics Committee, Social Research <srec@ucc.ie> 18 January 2018 at 13:52
To: Larkin Cunningham <larkin.cunningham@gmail.com>

Dear Larkin

The Social Research and Ethics Committee has reviewed and approved your application Log 2017-133 entitled “A model for the design of game based learning activities” no resubmission required.

Please note the comments of the committee below regarding a suggested amendment to the letter as follows

- His sentence is: Approval must be given by the Social Research Ethics Committee of UCC before studies like this can take place
    - ➢ Proposed change: Ethical approval has been granted by the Social Research Ethics Committee of UCC

The committee wishes you every success with your research.

All the best

XXXXX (Name redacted)

A.2 Recruitment Emails

From: Larkin Cunningham
Sent: 25 April 2018 15:08
To: COMPUTING.LIST <COMPUTING.LIST@cit.ie>
Subject: Message to pass on to students

Hi all,

Can I ask all year coordinators to send on the following to their classes? Thanks.

Dear computer science students,

For those that don't know me, I'm Larkin Cunningham and I'm a lecturer here in the computer science department teaching a range of software development subjects, including games development.

I am running a study on virtual reality, game-based learning and learning analytics. I am looking for volunteers to take part in what should be an interesting and enjoyable experience playing a VR-based educational game. Detailed information about the study is available on the following web page:
http://larkin.io/index.php/vr-learning-analytics-study-information/

Virtual, Augmented and Mixed reality is an exciting area of research and a technology that will play an ever greater part in our lives over the coming years. This study is an opportunity to experience that technology first hand and see a real world application of the technology. You'll also see how video games, which I know many of you enjoy playing, intersects with education. I am happy to answer any queries you might have about VR and games development in general.

To express an interest in taking part in the study you can either fill in the form at the end of the webpage, or just email me: larkin.cunningham@cit.ie. I realise this is a very busy time of year and summer is fast approaching, but this is an opportunity for you to take a short break from your studies and project work and have a bit of fun and experience something new.

I will be running the study during the following times. Your participation time would be approx. 30 minutes:

Thursday, May 3rd, 9am to 1pm and 4pm to 6pm
Wednesday, May 9th - all day

However, the study will continue from now till the end of the summer and I can arrange just about any other time that suits you.

Regards,
Larkin Cunningham
B179
021 433 5744

From: Larkin Cunningham [mailto:Larkin.Cunningham@cit.ie]
Sent: Wednesday 25 April 2018 10:56
To: CIT@cit.ie
Subject: Study on Virtual Reality, Game-based Learning and Learning Analytics

Hi all,

I will be running a study on the use of **VR, game-based learning and learning analytics** from now until the end of the summer.

Information about the study is available here:
http://larkin.io/index.php/vr-learning-analytics-study-information/

Anyone can take part. Not only should participating be fun, but it would allow you to experience first-hand how VR technology can be applied to education. Those of you involved in teaching will be interested in the use of learning analytics to see how students perform tasks / exercises. Or maybe you just want to experience VR for yourself and see what all the hype is about.

If you are interested in taking part in the study (about 30 minutes of your time), you can submit the form on my web page or just reply to this email.

I will be running the study all the way through to the end of the summer. For academic staff, I can arrange a suitable time before the summer break, e.g. during exam weeks or just about any time before mid-June.

Regards,

Larkin Cunningham
Computer Science Lecturer
Cork Institute of Technology
Tel: +353 21 433 5744
Office: B179
Ext: 5744

A.3 Information Sheet

This information sheet was made available via the website, http://larkin.io. After the line, “Some of my early VR prototyping” (page 1), there was an embedded Youtube video featuring example gameplay mechanics. The information sheet features hyperlinks that link to explanations of the terminology used.

VR & LEARNING ANALYTICS STUDY

LARKIN CUNNINGHAM, COMPUTER SCIENCE DEPT., CIT

Overview

This study is being undertaken as part of my research into:

- Game-based Learning
- Virtual Reality
- Learning Analytics
- Visualization of learning

as part of the requirements for a PhD in Digital Humanities at UCC.

What is involved?

You will wear an Oculus Rift Virtual Reality headset and use touch controllers to navigate and interact with objects in a game that teaches some fundamentals of graph theory. The game is immersive and you will see virtual hands and be able to manipulate objects with them. The game lasts about 15 minutes. You will spend about another 15 minutes completing a questionnaire.

Do I need any prior knowledge or experience?

Absolutely none. After a brief orientation with the VR technology, you will begin playing the game. The game has a tutorial that guides you through how to use the controls. You do not need to know anything about graph theory or have any technical knowledge. Whether you are a CIT employee, a student, or anyone else of least the age of 18, you can take part.

What’s all this graph theory stuff anyway?

Put simply, it’s just about connecting related things together. You may have seen social network graphs, for example, that show how people are connected to each other. It is used in many other ways – visualization of business data, finding the shortest route on a map, natural language processing, studying molecules, and more. I have developed a set of game mechanics that could be applied to all of the above. The game only scratches the surface of graph theory, but hopefully gives a feeling for some of the possibilities.

Some of my early VR prototyping:

Where does Learning Analytics fit in with Game-based Learning?

Learning analytics can be used to improve student learning outcomes, engagement, improve retention and efficiently target interventions. While learning management systems like Blackboard have a wealth of data that can be analysed to identify students who are not engaging, it does not tell us very much about the ways in which students learn. Game-based learning offers us a chance to capture data as a student engages with game-based learning activities. Some of this data can be mapped to taxonomies of learning, such as the revised Bloom's or Biggs's SOLO, while other data allows us to reconstruct in real-time what a student did during an exercise. This allows for the possibility to visualize learning in several different ways. The data also allows for the possibility of personalized and adaptive learning – in other words, educational games that respond uniquely to each player.

How is data used in this study?

Many of your interactions in the game will be stored in a database using an API (application programming interface) I have developed. This will hopefully allow me to identify where players have difficulties in the game, verify that certain learning has taken place (mapped to Biggs's SOLO taxonomy), to be able to replay in real-time how you carried out the exercises in the game, and to visualize how each player progressed to identify players who struggled to complete the exercises.

What happens to my data?

All data will be kept confidential for the duration of the study and is available only to me and my supervisor. No clues to your identity will appear in the thesis. You will be asked to sign a consent form to indicate you understand what will happen with your data.

Are there any disadvantages to me taking part?

I do not envisage any negative consequences to you taking part in the study. Some users of VR headsets have reported mild symptoms of VR / motion sickness. However, this is usually related to games that allow free movement, whereas I have designed the game to minimize or eliminate these symptoms by implementing "teleportation".

Who has reviewed this study?

Approval must be given by the Social Research Ethics Committee of UCC before studies like this can take place. If you need any further information, you can contact me: Larkin Cunningham, 021 433 5744, larkin.cunningham@cit.ie. My supervisor, Dr. Orla Murphy, can be contacted by email at o.murphy@ucc.ie.

A.4 Consent Form

CONSENT FORM

University College Cork, Ireland
Coláiste na hOllscoile Corcaigh

I………………………………………agree to participate in Larkin Cunningham's research study.

The purpose and nature of the study has been explained to me in writing.

I am participating voluntarily.

I give permission for you to ask me to fill in a questionnaire and for you to take observational notes.

I understand that I can withdraw from the study, without repercussions, at any time, whether before it starts or while I am participating.

I understand that I can withdraw permission to use the data within two weeks of my participation, in which case the material will be deleted.

I understand that anonymity will be ensured in the write-up by disguising my identity.

I understand that disguised extracts from my responses to questions in the questionnaires may be quoted in the thesis and any subsequent publications if I give permission below:

(Please tick one box:)

I agree to quotation/publication of extracts from my responses ☐

I do not agree to quotation/publication of extracts from my responses ☐

Signed: ……………………………………. Date: ………………..

PRINT NAME: …………………………………….

A.5 Research Protocol

Research Protocol for initial trial study into Game Based Learning, VR, and Analytics

Lab-based protocol

Participants are initially asked to confirm they understand what the study entails having read the information sheet. They are then asked to sign a consent form.

Task 1:

The first task in the experiment is the playing of the VR game. A think aloud protocol will be in place during this task. The researcher explains the think aloud protocol to the participant as follows:

"As you play the game you may have thoughts you would like to convey about your experience within the game. You may verbalise these thoughts by speaking them. I will take notes when you speak. I will also be observing your game play on another screen and may make notes based on observations from the screen. There may be times in the game when you are unsure of the next action to take. Because the nature of the study is to gather gameplay data as accurately as possible, intervention to help you will only take place after a sufficient amount of time has passed and it is obvious from what is observed on the screen that assistance must be given in order for the game to proceed to the next stage. Any such interventions will be noted."

Before the first task begins a brief introduction is given about how to use the VR headset and controllers. The researcher then starts the VR game and dons the headset to enter a random number code that will later be used to link the game data to the questionnaire responses. Once this is done, the researcher takes off the headset and helps the participant to comfortably don the headset. The participant is then instructed to continue playing the game and following the in-game instructions. At the end of the game the player will remove the headset.

Task 2:

When gameplay has ceased, data should have been gathered in a database via an API. The second task is to load a web-based dashboard in the browser and show three sets of visualizations to the participant: a list of badges achieved and not achieved, a leaderboard showing the players time and position for the timed exercise in the game, a visualization of learning outcomes from the game where the researcher briefly explains Biggs's SOLO Taxonomy, and an experimental visualization of exercise performance. The researcher navigates the prototype web-based dashboard and asks the participant if he or she is ready to proceed to the next visualization each time.

Task 3:

The researcher then asks the participant to take a seat at a table and hands the participant a questionnaire to complete. The random number id entered in the game is written at the top of the questionnaire. The participant is then asked to complete the questionnaire.

Once the participant leaves, the database is backed up.

A.6 Questionnaire

POST-GAMEPLAY QUESTIONNAIRE

Thank you for taking the time to play The Graph Game. The reasons for filling in the questionnaire are covered on the information sheet that was provided. How the data will be used was also covered on that information sheet and you should already have signed a consent form.

Random ID Number: ________________________________ (to be filled in by the researcher)
(Note: the random id number is used to match your responses in this questionnaire to the data gathered during gameplay for cross-referencing purposes)

A1. Gender? ☐ Female ☐ Male ☐ Transgender ☐ Other ☐ Prefer not to say

A2. How old are you?

☐ 18 – 24 ☐ 25 – 34 ☐ 35 – 44

☐ 45 – 54 ☐ 55 – 64 ☐ 65 and older

A3. What is your level of education?

☐ Lower secondary or less (junior / inter cert or primary education)

☐ Upper secondary (leaving cert or equivalent)

☐ NFQ Level 6 (e.g. higher / national certificate or FETAC L6)

☐ Ordinary or Honours Bachelor (NFQ Level 7 or 8)

☐ Masters / Postgrad Diploma (NFQ Level 9)

☐ Doctorate (NFQ Level 10)

A4. Provide a brief description of your employment status, e.g. "full-time student of computer science" or "lecturer in economics" or "retired construction worker":

A5. How often do you play video games?

At some point during the course of:

- ☐ less than 1 day per year
- ☐ 1 to 7 days per year
- ☐ 8 to 28 days per year
- ☐ 29 to 100 days per year
- ☐ at least 101 days per year

A6. Are you involved in teaching, lecturing, instructional design or a similar profession in the education sector?

- ☐ Yes
- ☐ No

A7. How much knowledge of graph theory do you have?

- ☐ None
- ☐ A little – it was covered a little bit as part of my studies or research
- ☐ A lot – I studied a module where graph theory was significantly explored
- ☐ Don’t know / not sure

SECTION B – Learning Outcomes

To what extent do you disagree or agree with the following statements having participated in the game based learning activities?

Code	Statement	Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
B1	I think I have a better understanding of the fundamentals of graph theory having participated in the game based learning activities	☐	☐	☐	☐	☐
B2	I think I can see applications of graph theory in the real world / industry having participated in the game based learning activities	☐	☐	☐	☐	☐
B3	Participating in the game based learning activities has stimulated my interest in graph theory	☐	☐	☐	☐	☐
B4	The game did not help me to understand graph theory and how it might be applied	☐	☐	☐	☐	☐

SECTION C – Motivational Outcomes

To what extent do you disagree or agree with the following statements having participated in the game based learning activities?

Code	Statement	Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
C1	I enjoyed participating in the game based learning activities	☐	☐	☐	☐	☐
C2	Participating in these game based learning activities has motivated me to take part in more game based learning activities	☐	☐	☐	☐	☐
C3	Participating in the game based learning activities has made me less likely to try game based learning in the future	☐	☐	☐	☐	☐

SECTION D – Efficiency Outcomes

To what extent do you disagree or agree with the following statements having participated in the game based learning activities?

Code	Statement	Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
D1	I think these game based learning activities are a quick way to learn about the fundamentals of graph theory	☐	☐	☐	☐	☐
D2	I think these game based learning activities will just waste time I could spend using other resources	☐	☐	☐	☐	☐

SECTION E – Progression of Understanding

To what extent to do you disagree or agree with the following statements having participated in the game based learning activities?

Code	Statement	Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
E1	The game based learning activities helped me to progress through levels of understanding, from understanding simple concepts to more complex activities	☐	☐	☐	☐	☐
E2	The visualization in the web-based dashboard of progression of understanding according to Biggs's SOLO taxonomy was "clear and understandable"	☐	☐	☐	☐	☐
E3	The visualization in the web-based dashboard of progression of understanding according to Biggs's SOLO taxonomy was "useful and lets me know where I stand"	☐	☐	☐	☐	☐
E4	I did not get a sense of how my learning was progressing	☐	☐	☐	☐	☐

SECTION F – Formative Feedback

To what extent to do you disagree or agree with the following statements having participated in the game based learning activities?

Code	Statement	Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
F1	The game based learning activities let me know promptly whether I was doing things correctly	☐	☐	☐	☐	☐
F2	By the end of the game based learning activities, the game had given me an indication of how well I was doing	☐	☐	☐	☐	☐
F3	The leaderboard in the web-based dashboard gave me an idea of where I stood overall in comparison to others for the final exercise	☐	☐	☐	☐	☐
F4	I did not get a sense of how I was doing as I played the game	☐	☐	☐	☐	☐
F5	I did not get a sense of how I had done after completing the game	☐	☐	☐	☐	☐
F6	I found the award of achievements / badges motivating	☐	☐	☐	☐	☐
F7	Having viewed my list of badges in the dashboard, I would be motivated to retry activities to gain badges I was missing	☐	☐	☐	☐	☐
F8	I would be fine with allowing other students to see my collection of badges	☐	☐	☐	☐	☐
F9	Being able to see other students' collections of badges would motivate me to earn more badges through game based learning activities	☐	☐	☐	☐	☐

SECTION G – Additional Uses of Captured Gameplay Data

As part of the game-based learning platform being developed for this research, the ability for teachers / lecturers to replay student activities in real-time (or speeded up, slowed down and paused) will be added so that not just a final outcome is available, but also how the outcome was achieved (thanks to data being stored for every action). With that in mind, **to what extent do you disagree or agree with the following statements?**

Code	Statement	Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
G1	Having my teacher or lecturer able to see exactly how I performed a task gives me more confidence that he / she will be able to more accurately assess my work	☐	☐	☐	☐	☐
G2	I would be more likely to repeat an exercise if I could see my improvements visualized (e.g. faster time or fewer steps), such as on a chart comparing all previous efforts	☐	☐	☐	☐	☐
G3	I would rather that my teacher or lecturer cannot see the steps I make along the way to my final answer	☐	☐	☐	☐	☐

Provide a response to G3, G4, G5 and G6 if you have any teaching, tutoring or instructional design experience, otherwise skip to section H:

Code	Statement	Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
G4	As an instructor, I would like the ability to see the steps by which a student reached an answer / solution rather than just seeing the final answer	☐	☐	☐	☐	☐
G5	As an instructor, being able to see the steps by which a student reached an answer could help me to assess / mark their effort more accurately	☐	☐	☐	☐	☐
G6	Having a dashboard with visualizations representing learning statistics / how my students perform would be something I would view often	☐	☐	☐	☐	☐
G7	A visualization dashboard would be of little use to me	☐	☐	☐	☐	☐

SECTION H – VR-Specific Questions

H1. What experience of VR do you have?

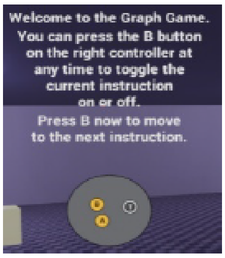
☐ I have never used it prior to playing this game

☐ I used VR on less than 4 prior occasions

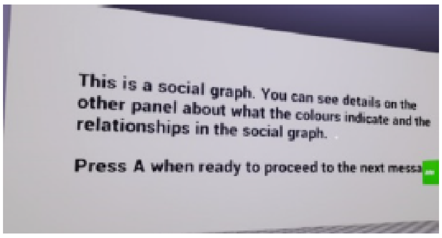
☐ I have used VR frequently or I own a VR headset (e.g. Gear VR, Oculus Rift, HTC Vive, PSVR)

H2. Which approach to presenting messages or instructions did you prefer?

☐ Having them float in front of me and visible wherever I looked



☐ On the walls where I had to stop and read the instructions



☐ No preference

Optional – a brief comment on how instructions were presented or how you would like them presented:

H3. Did you experience any discomfort using VR in the game, e.g. dizziness or any other unpleasant physical or psychological feelings?

☐ Yes ☐ No

If you answered yes, would you mind giving a brief description of the discomfort felt (you don't need to, if you prefer not to say)?

SECTION I – Universal Design for Learning

To what extent do you disagree or agree with the following statements having participated in the game based learning activities?

Code	Statement	Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
I1	Assuming I had time to master the controls and mechanics of the game, I would be happy for the exercises I perform in the game to be assessed as part of my overall grade	☐	☐	☐	☐	☐
I2	Having a choice of either completing assessments in a game such as this or on paper is a good idea	☐	☐	☐	☐	☐
I3	Being able to see graphs represented in an immersive 3D environment (VR) in addition to traditional 2D representations (such as on PowerPoint slides or in a book) could help improve the way I learn about the subject	☐	☐	☐	☐	☐
I4	I have enough ways of accessing materials without adding game-based materials and activities to the mix	☐	☐	☐	☐	☐
I5	Being able to engage with the material (fundamentals of graph theory) in this game could help sustain my enthusiasm for the subject when added to other materials (on paper, slides, videos, etc.)	☐	☐	☐	☐	☐
I6	The "hands on" nature of the game (being able to move around, grab objects, and so on) suits my way of learning (as opposed to, for example, introspection / contemplation)	☐	☐	☐	☐	☐
I7	I would be more interested in reading about graph theory (in books, slides, etc.) than engaging in a game-based learning approach to teaching graph theory	☐	☐	☐	☐	☐

Code	Statement	Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
I8	More visualizations, such as the ones provided in the web-based dashboard, would help me to gauge my progress over time	☐	☐	☐	☐	☐
I9	The timed graph completion exercise challenged me positively in a way I am not used to when engaging in traditional learning activities	☐	☐	☐	☐	☐
I10	The timed graph completion exercise made me feel uncomfortable or bored and I would rather not do a similar game-based exercise again	☐	☐	☐	☐	☐
I11	The provided graph examples, such as the social graph (people, books and publishers) and the natural language graph, made what I learned relevant and/or relatable to my prior knowledge	☐	☐	☐	☐	☐
I12	The instructions were provided step-by-step in easy to digest "chunks"	☐	☐	☐	☐	☐
I13	The sequence of tasks allowed me to build towards a mastery of the concepts presented	☐	☐	☐	☐	☐
I14	The instructions ramped up in difficulty too fast and I ended up feeling lost by the end	☐	☐	☐	☐	☐

A.7 Questionnaire Modifications

Because of the iterative approach to the study, modifications were made after the first cohort of participants (N=7). The modified questionnaire was administered to the second cohort of participants (N=7).There were no modifications for the final cohort (N=6).

The following questions, H2 to H6, were added, with H2 from the original questionnaire removed. H3 in the original questionnaire became H7 in the updated questionnaire.

To what extent do you disagree or agree with the following statements?

Code	Statement	Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
H2	The instructions displayed in the VR world were easy to find	☐	☐	☐	☐	☐
H3	The instructions displayed in the VR world were easy to read	☐	☐	☐	☐	☐
H4	I frequently had to spend time searching for the next instruction	☐	☐	☐	☐	☐
H5	Once I had completed the tutorial level, I had no difficulties interacting with the VR world and the graphs	☐	☐	☐	☐	☐
H6	There was a steep learning curve getting to grips with Virtual Reality compared to other media	☐	☐	☐	☐	☐

The following question, I15 was added to the end of the questionnaire.

I15	The exercise performance visualizations, when fully developed, are something I would refer to frequently	☐	☐	☐	☐	☐

A.8 Example Observational Notes

854 212

problem with focusing on text - wall text wasn't much better.

didn't know where B was, had to remove head set.

Trouble with using index finger
used middle finger.

grabbed too early
so did 2nd participant

Looked at controls text
rather than rules text
had turned around
but didn't
notice the
rules text
was
different

needed to
consult controls text
to work out connecting

when
grabbing
incorrectly
connected
cube goes back
to green

liked
graph "cool effect"

difficulty reading text
real world 2

Brings the
cubes with
him to
make them
closer

needed feedback

would like to
see whole
graph

recognises
nature of VR/3D

First real world
example "makes
sense"

moved
everything
into frame

read out sample sentences.
spent lot of time trying to figure out all sentences.

Problem reading text exercise 2. — nearly lost balance.

Level 2 exercise - began by bringing all cubes closer

Waved around cube to see connections move + see what was missing

L3 pressed A instead of B

Quickly shaking cubes "feels weird"

What is "baked-in"?

A.9 Semi-structured Observation Form

Participant ID:

Date / Time:

Location:

Category	**(Stage) Observation**
Usability / Accessibility (UA)	1. 2. 3.
Strategies Employed (SE)	1. 2. 3.
Pedagogical (P)	1. 2. 3.
Other (O)	1. 2. 3.

Additional Notes:

Stage refers to when the observation took place and is one of:

- B - Before first instruction
- T – Controls / Mechanics Tutorial
- E1 – Exercise 1 (colour matching)
- RW1 – Real-world example 1
- RW2 – Real-world example 2
- E2 – Exercise 2 (animals / species taxonomy)
- E3 – Exercise 3 (synonyms and phrases)
- A – After E3 is complete
- O – Other, with explanatory note

A.10 Example Filled-in Observation Form

Participant ID: 384327

Date / Time: 03-May-2018 10:15

Location: Melbourn Training Room

Category	(Stage) Observation
Usability / Accessibility	1. (T) Wondering what the trigger is 2. (T) Wasn't looking for the yellow cube despite instruction 3. (T) Didn't realise the red dot was there for aiming 4. (T) Managed to grab cube at second attempt 5. (E1) Asked about toggling the red connection / edge 6. (RW1) May have missed the 2nd message (hit A twice?) 7. (E3) Participant wondered out loud if had more than 90 seconds, thinking that maybe the 90 seconds was a cut-off: participant was informed that this was not the case 8. (O) Throughout, issues with distance of red dot – at times trying to select something that was too far away, i.e. when dot was still white 9. (E3) Accidentally disconnected a correct connection made (Shopping →List); almost certainly a mistake with selection controls 10. (O) Stepping over the wires to the HMD quite a lot – this could be solved by ensuring the participant understands how to redirection after a teleport
Strategies Employed	1. (O) Participant teleported about and made connections 2. (E2) Very methodical – took time to ensure connections were correct before committing to them; as a result no mistakes were made 3. (E3) Very, very methodical, took time – only one mistake made near the end
Pedagogical	1. (RW1) Spent quite a while engaging at the example 2. (E2) Didn't seem to understand exercise instructions – had to remind participant to read the hint 3. (A) Participant commented about how hands on it was and that participant likes learning that way

Other	None

Additional Notes:

None

Stage refers to when the observation took place and is one of:

- B - Before first instruction
- T – Controls / Mechanics Tutorial
- E1 – Exercise 1 (colour matching)
- RW1 – Real-world example 1
- RW2 – Real-world example 2
- E2 – Exercise 2 (animals / species taxonomy)
- E3 – Exercise 3 (synonyms and phrases)
- A – After E3 is complete
- O – Other, with explanatory note

Appendix B

The Practitioner Study Documents

B.1 Online Survey

Document begins overleaf.

The Adaptive Model for DGBL / VR Graph Game

Overview and Informed Consent

The following survey asks some open-ended questions related to a digital game-based learning (DGBL) analytics platform, and the case study of a virtual reality (VR) game that teaches graph theory.

The research is being carried out as part of Larkin Cunningham's PhD in Digital Humanities in UCC. The purpose of the research is to discover if the platform and the game developed, and the methodology used to develop the game, have been successful and if there are areas for improvement.

You are being asked to complete the survey because you attended a demonstration of the platform and the VR game, including various visualizations of learning through a dashboard, and you have expertise in a related area.

The survey data will be analysed and the results of that analysis and selected quotations will be referenced in the PhD thesis. All data will be kept confidential for the duration of the study and is available only to Larkin (larkin.cunningham@cit.ie) and his supervisor (Dr. Orla Murphy, Digital Humanities, UCC, o.murphy@ucc.ie). No clues to your identity will appear in the thesis. You will be asked to provide consent to indicate that you understand what will happen with your data. This survey is being conducted according to the "Code of Good Practice in Research" published by Cork Institute of Technology (CIT) (where I work as a lecturer in computer science), which are approved by CIT's research ethics committee (REC) and follows on from a similar study conducted with learners approved by UCC's Social Research Ethics Committee (SREC).

Read the following statements regarding informed content and if you agree, enter your name below to indicate that you do.

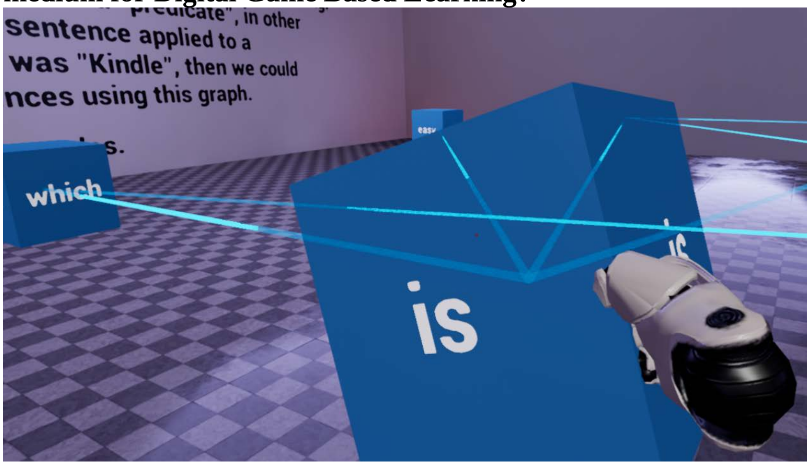
- The purpose and nature of the study has been explained to me in writing (see text above).
- I am participating voluntarily.
- I understand that I can withdraw permission to use the data within two weeks of my participation, in which case the material will be deleted.
- I understand that anonymity will be ensured in the write-up by disguising my identity.
- I understand that disguised extracts from my responses to questions in the questionnaires may be quoted in the thesis and any subsequent publications.

1. Enter your name to indicate your agreement to take part

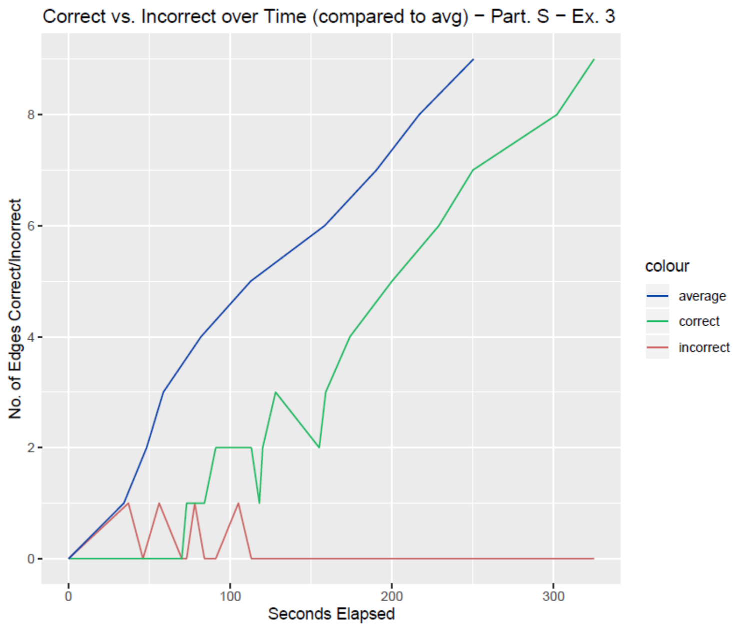
2. Please provide a brief description of the duties you perform in your job (optionally include your job title), particularly those related to aspects of this research.

3. What are your thoughts on the effectiveness of digital game-based learning?

4. What benefits do you think there are or might be in using Virtual Reality as a medium for Digital Game Based Learning?



5. What are your thoughts on the benefits or otherwise of Learning Analytics Dashboards (such as the one containing visualizations of learning, badges, leaderboard demonstrated to you earlier) ...



... from the perspective of learner and educator?

6. The platform allows games (like the VR graph game) to send "learner interaction" events to a central API - this includes learning paths mapped to the SOLO taxonomy (or any other taxonomy, such as Bloom's).

Your learning mapped to Biggs's SOLO Taxonomy

Click here for a breakdown of the taxonomy

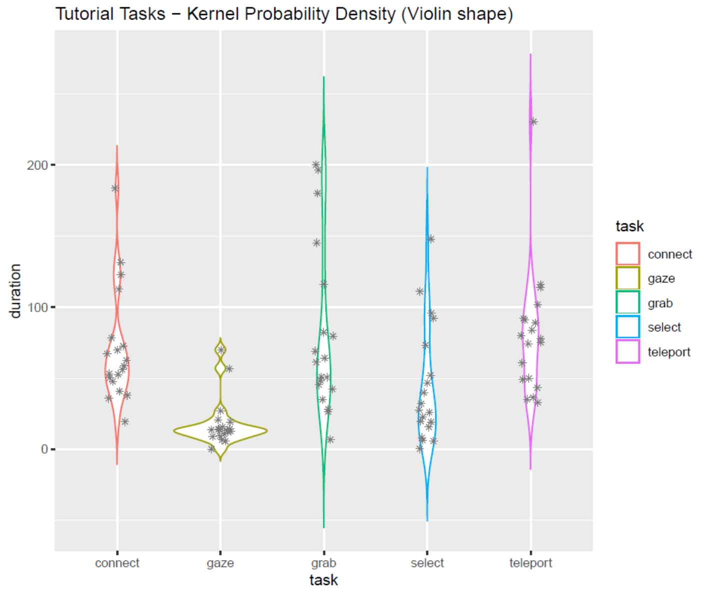
Learning Outcome	Complexity	Completion
1..... Demonstrate an understanding of the fundamentals of graph theory	Relational	67%
1.1......... Understand what a vertex and node is	Unistructural	✓
1.2......... Connect vertices with an edge	Multistructural	✓
1.3......... Calculate the shortest path using an appropriate algorithm	Relational	
2..... Complete graphs from sets of rules	Relational	100%
2.1......... Complete a graph according to a simple rule	Multistructural	✓
2.2......... Complete a word graph according to a complex rule	Relational	✓
3..... Apply graph theory fundamentals to real world problems	Extended Abstract	50%
3.1......... Manipulate example graphs representing the real world	Multistructural	✓
3.2......... Construct a graph that represents a real world problem	Extended Abstract	

This allows for visualization of learner progress. What are your thoughts on this approach?

Part of my thesis involved developing what is called the Adaptive Model for Digital Game Based Learning. It is built on best practices in the development of DGBL, such as the principles of agile software development, the universal design for learning (UDL) framework, and formative and summative evaluation using well-established models, such as the learning mechanics - game mechanics (LM-GM) for serious games, Csikszentmihalyi's theory of flow, Shell's lens of challenge, and the mapping of learning to data using taxonomies such as Biggs's SOLO and revised Bloom's. These questions focus on the model.

7. What are your thoughts on having frequent iterations (and functional prototypes) during design and development of instructional materials (including games), and including key stakeholders like educators and learners at the end of each iteration (to trial prototypes)?

8. As well as using visualizations to provide learners and educators with information about how learners are doing (performance, engagement, etc.), they can be used during development to help with formative evaluation of the game, such as discovering usability issues or balance issues (exercises too easy or too hard). The example here identifies several (slightly worrying) outliers with the grab mechanic, for example.



What are your thoughts on whether this is a significant improvement to the way learning games are developed?

9. The [Universal Design for Learning framework]() has 31 checkpoints for how learning can be made more universal, including catering for those with disabilities, but also all learners to empower them to be more autonomous and self-regulating, for example. What are your thoughts on having the UDL framework at the centre of a model for developing DGBL solutions?

10. The methodology used to evaluate the VR Graph Game (formatively and summatively) involved observational notes, captured gameplay data and post-play questionnaire, allowing for triangulation of findings to improve confidence. An example is that observations noted that some learners had depth perception issues when grabbing objects, something the visualization (the violin plot with outliers) of gameplay data in a previous question showed was a problematic game mechanic. What are your thoughts on this? Is it ideal or overkill, etc.?

B.2 Sample Participant Recruitment Email

Dear Dr. XXXXXX,

I am approaching you to see if you would like to take part in a study I am doing of subject matter experts in the area of GBL / VR. This research is for my PhD in Digital Humanities at UCC, which I am nearing the end of (I am also a computer science lecturer in Cork Institute of Technology).

The study would involve you watching an online video, which I hope you would find interesting, and filling in an online questionnaire with 8 questions (usually a short paragraph answer per question is sufficient).

The video demonstrates a VR game-based learning solution that teaches the maths/computer science subject of graph theory. It's at a fundamental level, so no knowledge of graph theory is at all necessary, plus it is all taught in a very visual, hands-on way. Once the demo of gameplay is finished, in the video I talk through a number of visualizations presented in a web-based learning analytics dashboard.

Because it is all online, you could do it at a time that suits.

The link to the video and survey is: https://www.surveymonkey.com/r/W5NS73G

I'm sure you are very busy, but your insight given your background would be very welcome.

Yours faithfully,

Larkin Cunningham
Computer Science Lecturer
Cork Institute of Technology
Tel: +353 21 433 5744
Office: B179
Ext: 5744

B.3 The Demonstration Video

The video provided to remote participants can be viewed by visiting the following hyperlink:

https://www.youtube.com/watch?v=dHEfLIeG0Ls

Appendix C

API Endpoint Specifications

This appendix lists, one per page, the API endpoints used only for this research. Other endpoints would be added depending on requirements. Endpoint parameters are contained in braces. For example, `{userToken}` can be replaced by a value for the userToken parameter.

C.1 Verify Game Registration

Endpoint:

GET /api/learner/gameRegistration/{game}/{userToken}/exists

Description:

Verifies whether, for a given game label and user token, a game registration object exists.

Parameters:

Parameter	Description	Data Type
game	unique game label	String
userToken	user token (unique external id)	String

Returns:

```
{
  "response": "boolean_string"
```

```
}
```

C.2 Get List of Badges

Endpoint:

GET /api/learner/gameRegistration/{game}/{userToken}/exists

Description:

Gets a list of badges for a game registration.

Parameters:

Parameter	Description	Data Type
game	unique game label	String
userToken	user token (unique external id)	String

Returns:

```
[
  {
    "achieved": boolean,
    "description": "string",
    "game": "string",
    "label": "string",
    "timestamp": "date_time_string",
    "title": "string",
    "userToken": "string"
  }
]
```

C.3 Save Learner Interaction

Endpoint:

POST /api/learnerInteraction

Description:

Save a generic learner interaction.

Request Body:


```json
{
  "game": "string",
  "key": "string",
  "timestamp": "date_time_string",
  "type": "string",
  "userToken": "string",
  "value": "string"
}
```

C.4 Get Learner Interactions for Type

Endpoint:

GET
/api/learnerInteraction/game/{game}/userToken/{userToken}/type/{type}[?all]

Description:

Get all learner interactions for a give learner interaction type for a game registration. For example, if type is `"learning_outcome"`, all learning outcomes completed will be returned for the provided game registration.

Parameters:

Parameter	Description	Data Type
game	unique game label	String
userToken	user token (unique external id)	String
type	learner interaction type	String
all	optional URL parameter (see note below)	N/A

Returns:

```
{
  "learnerInteractions": [
    {
      "id": integer,
      "key": "string",
      "version": integer,
      "value": "string",
      "timestamp": "date_time_string"
    }
  ]
}
```

Note: `version` is a sequence allowing for multiple values of a learner interaction type. An example is a challenge score: the learner might retry a challenge to better a previous score and `version` allows the sequence of attempts to be stored. If the `all` parameter is missing, only the latest value is returned.

C.5 Get Specific Learner Interaction

Endpoint:

GET /api/learnerInteraction/game/{game}/userToken/{userToken}/type/{type}/key/{key}

Description:

Get a specific learner interaction for a given type and key for a game registration. For example, if type is `"score"` and the key is `speed_run_1`, the value for the timed challenge will be returned.

Parameters:

Parameter	Description	Data Type
game	unique game label	String
userToken	user token (unique external id)	String
type	learner interaction type	String
key	learner interaction key	String
all	optional URL parameter (see note under Section C.4)	N/A

Returns:

```
{
  "learnerInteractions": [
    {
      "id": integer,
      "key": "string",
      "version": integer,
      "value": "string",
      "timestamp": "date_time_string"
    }
  ]
}
```

C.6 Get Leaderboard for Key

Endpoint:

GET /api/learnerInteraction/leaderboard/game/key/all

Description:

Get all learner scores for a game's challenge. The learner interaction type is assumed to be `"score"`.

Parameters:

Parameter	Description	Data Type
game	unique game label	String
key	learner interaction key	String

Returns:

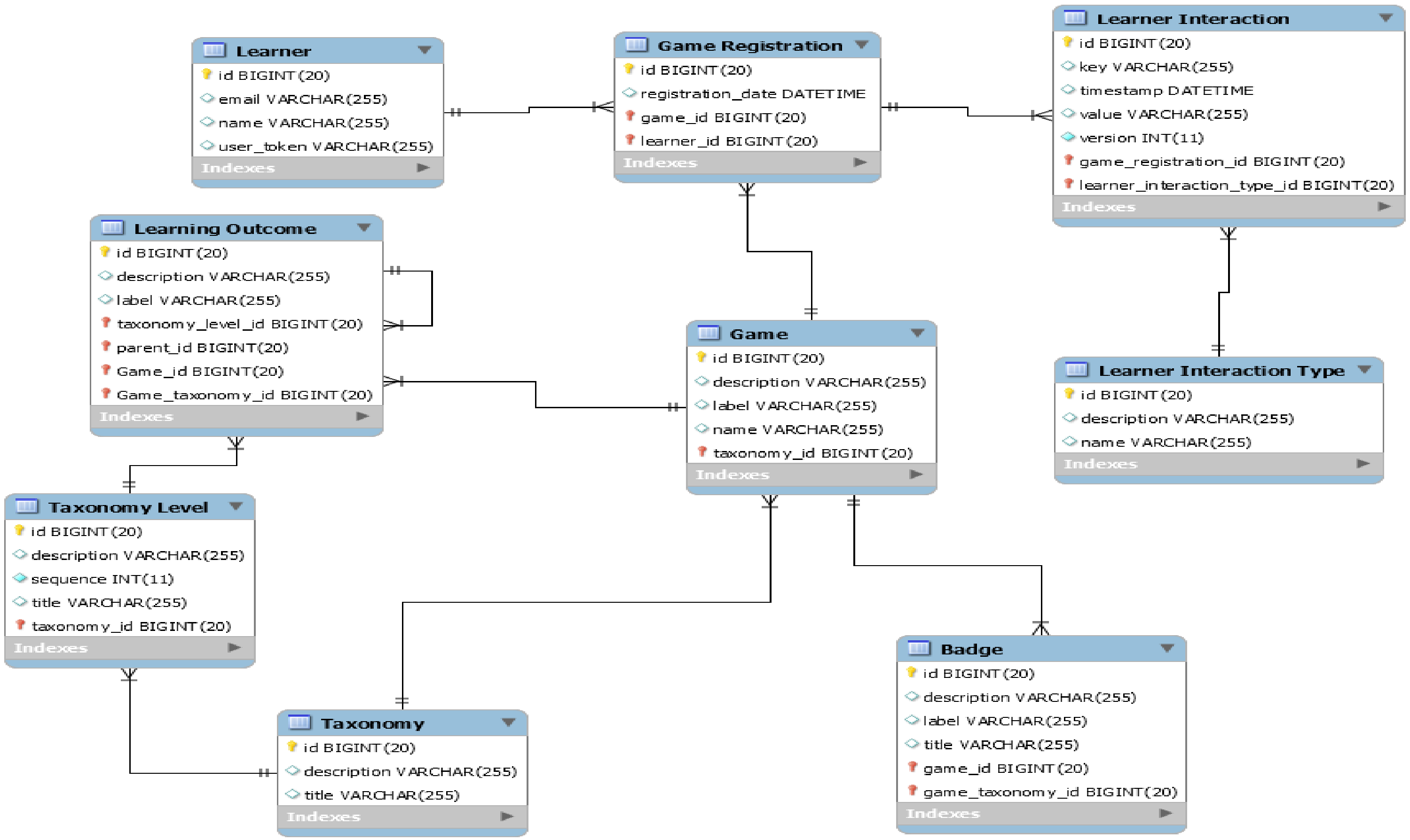
```
{
  "count": integer,
  "learnerScores": [
    {
      "position": integer,
      "score": decimal,
      "userToken": "string"
    }
  ]
}
```

Appendix D

Source Code Listings and Diagrams

D.1 Entity Relationship Diagram

Diagram is overleaf.


Learner
id BIGINT(20)
email VARCHAR(255)
name VARCHAR(255)
user_token VARCHAR(255)
Indexes
Game Registration
id BIGINT(20)
registration_date DATETIME
game_id BIGINT(20)
learner_id BIGINT(20)
Indexes
Learner Interaction
id BIGINT(20)
key VARCHAR(255)
timestamp DATETIME
value VARCHAR(255)
version INT(11)
game_registration_id BIGINT(20)
learner_interaction_type_id BIGINT(20)
Indexes
Learning Outcome
id BIGINT(20)
description VARCHAR(255)
label VARCHAR(255)
taxonomy_level_id BIGINT(20)
parent_id BIGINT(20)
Game_id BIGINT(20)
Game_taxonomy_id BIGINT(20)
Indexes
Game
id BIGINT(20)
description VARCHAR(255)
label VARCHAR(255)
name VARCHAR(255)
taxonomy_id BIGINT(20)
Indexes
Learner Interaction Type
id BIGINT(20)
description VARCHAR(255)
name VARCHAR(255)
Indexes
Taxonomy Level
id BIGINT(20)
description VARCHAR(255)
sequence INT(11)
title VARCHAR(255)
taxonomy_id BIGINT(20)
Indexes
Badge
id BIGINT(20)
description VARCHAR(255)
label VARCHAR(255)
title VARCHAR(255)
game_id BIGINT(20)
game_taxonomy_id BIGINT(20)
Indexes
Taxonomy
id BIGINT(20)
description VARCHAR(255)
title VARCHAR(255)
Indexes

D.2 API Database Schema SQL

The following SQL script can be used to create the tables for the API Database. The version used was MySQL 5.7.20, but it should work for any MySQL version 5 or greater database. Note that the tables were created by Hibernate—Java entity classes were written for the API Spring Boot application using JPA annotations for associations (foreign keys) and unique indexes.

Listing D.1: Schema.sql

```sql
-- MySQL dump 10.13  Distrib 5.7.20, for Win64 (x86_64)
--
-- Host: localhost    Database: rest_test_study2
-- ------------------------------------------------------
-- Server version   5.7.20-log

/*!40101 SET @OLD_CHARACTER_SET_CLIENT=@@CHARACTER_SET_CLIENT */;
/*!40101 SET @OLD_CHARACTER_SET_RESULTS=@@CHARACTER_SET_RESULTS */;
/*!40101 SET @OLD_COLLATION_CONNECTION=@@COLLATION_CONNECTION */;
/*!40101 SET NAMES utf8 */;
/*!40103 SET @OLD_TIME_ZONE=@@TIME_ZONE */;
/*!40103 SET TIME_ZONE='+00:00' */;
/*!40014 SET @OLD_UNIQUE_CHECKS=@@UNIQUE_CHECKS, UNIQUE_CHECKS=0 */;
/*!40014 SET @OLD_FOREIGN_KEY_CHECKS=@@FOREIGN_KEY_CHECKS, FOREIGN_KEY_CHECKS=0 */;
/*!40101 SET @OLD_SQL_MODE=@@SQL_MODE, SQL_MODE='NO_AUTO_VALUE_ON_ZERO' */;
/*!40111 SET @OLD_SQL_NOTES=@@SQL_NOTES, SQL_NOTES=0 */;

--
-- Table structure for table `badge`
--

DROP TABLE IF EXISTS `badge`;
/*!40101 SET @saved_cs_client     = @@character_set_client */;
/*!40101 SET character_set_client = utf8 */;
CREATE TABLE `badge` (
  `id` bigint(20) NOT NULL AUTO_INCREMENT,
  `description` varchar(255) DEFAULT NULL,
  `label` varchar(255) DEFAULT NULL,
  `title` varchar(255) DEFAULT NULL,
  `game_id` bigint(20) DEFAULT NULL,
  PRIMARY KEY (`id`),
```

```
  KEY `FKi43ktofkyr8gq8aldo1617tjp` (`game_id`)
) ENGINE=MyISAM AUTO_INCREMENT=7 DEFAULT CHARSET=utf8;
/*!40101 SET character_set_client = @saved_cs_client */;

--
-- Table structure for table `game`
--

DROP TABLE IF EXISTS `game`;
/*!40101 SET @saved_cs_client     = @@character_set_client */;
/*!40101 SET character_set_client = utf8 */;
CREATE TABLE `game` (
  `id` bigint(20) NOT NULL AUTO_INCREMENT,
  `description` varchar(255) DEFAULT NULL,
  `label` varchar(255) DEFAULT NULL,
  `name` varchar(255) DEFAULT NULL,
  `taxonomy_id` bigint(20) DEFAULT NULL,
  PRIMARY KEY (`id`),
  UNIQUE KEY `UK_4y7c8nirhd52unid41287rwlx` (`label`),
  KEY `FKsw44hcoh7dt3j4md4n8m0y7au` (`taxonomy_id`)
) ENGINE=MyISAM AUTO_INCREMENT=4 DEFAULT CHARSET=utf8;
/*!40101 SET character_set_client = @saved_cs_client */;

--
-- Table structure for table `game_registration`
--

DROP TABLE IF EXISTS `game_registration`;
/*!40101 SET @saved_cs_client     = @@character_set_client */;
/*!40101 SET character_set_client = utf8 */;
CREATE TABLE `game_registration` (
  `id` bigint(20) NOT NULL AUTO_INCREMENT,
  `registration_date` datetime DEFAULT NULL,
  `game_id` bigint(20) DEFAULT NULL,
  `learner_id` bigint(20) DEFAULT NULL,
  PRIMARY KEY (`id`),
  KEY `FKb2l85ewgnywbedu4jqprxbiau` (`game_id`),
  KEY `FKc81ta8ggr9rq58t9ennilp9yu` (`learner_id`)
) ENGINE=MyISAM AUTO_INCREMENT=106 DEFAULT CHARSET=utf8;
/*!40101 SET character_set_client = @saved_cs_client */;

--
-- Table structure for table `learner`
--

```

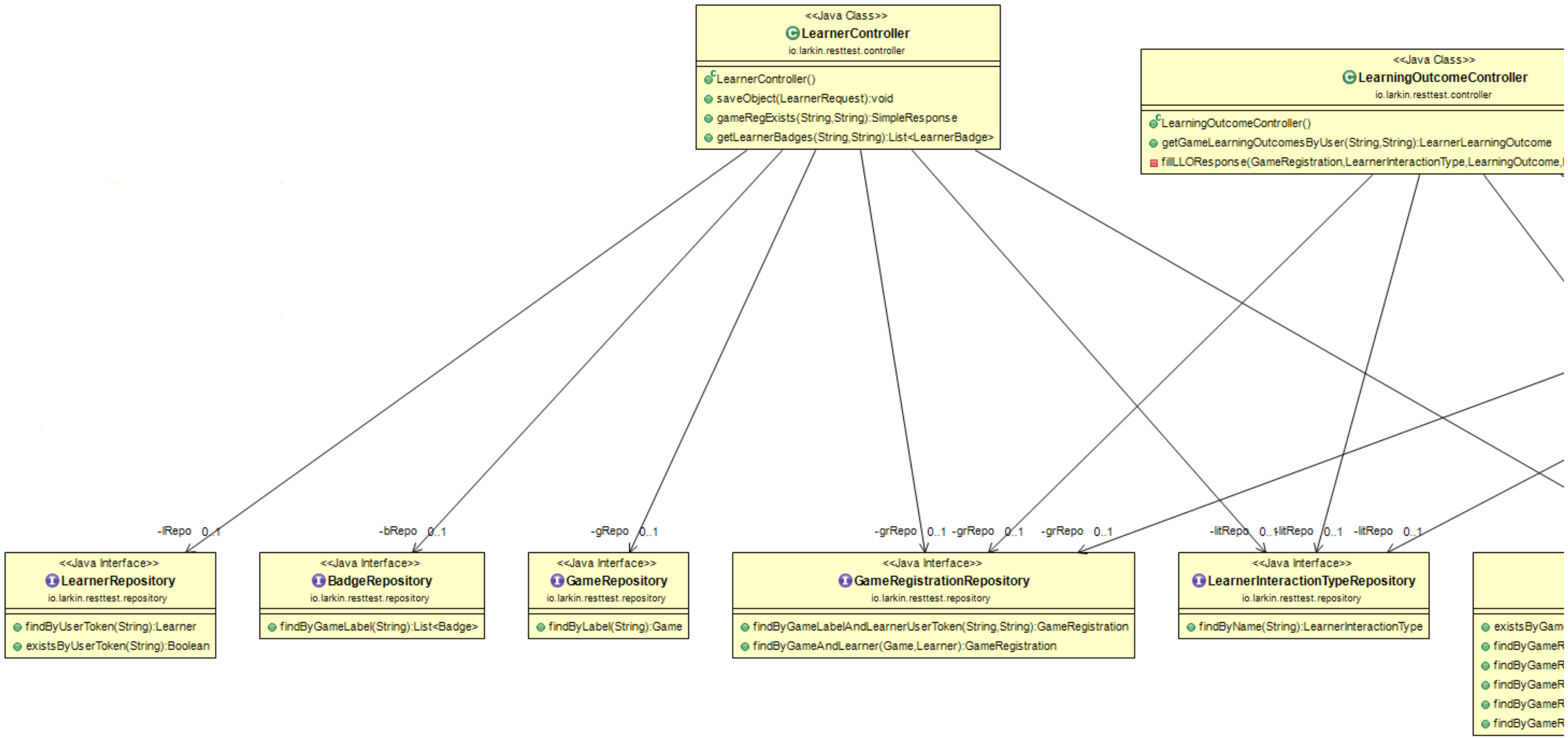
```
DROP TABLE IF EXISTS `learner`;
/*!40101 SET @saved_cs_client     = @@character_set_client */;
/*!40101 SET character_set_client = utf8 */;
CREATE TABLE `learner` (
  `id` bigint(20) NOT NULL AUTO_INCREMENT,
  `email` varchar(255) DEFAULT NULL,
  `name` varchar(255) DEFAULT NULL,
  `user_token` varchar(255) DEFAULT NULL,
  PRIMARY KEY (`id`),
  UNIQUE KEY `UK_ju0lseiik9kbo10wh7wxvtrsm` (`email`),
  UNIQUE KEY `UK_au0fyj321yuudln1hcc83ckpi` (`user_token`)
) ENGINE=MyISAM AUTO_INCREMENT=104 DEFAULT CHARSET=utf8;
/*!40101 SET character_set_client = @saved_cs_client */;

--
-- Table structure for table `learner_interaction`
--

DROP TABLE IF EXISTS `learner_interaction`;
/*!40101 SET @saved_cs_client     = @@character_set_client */;
/*!40101 SET character_set_client = utf8 */;
CREATE TABLE `learner_interaction` (
  `id` bigint(20) NOT NULL AUTO_INCREMENT,
  `key_` varchar(255) DEFAULT NULL,
  `timestamp` datetime DEFAULT NULL,
  `value` varchar(255) DEFAULT NULL,
  `version` int(11) NOT NULL,
  `game_registration_id` bigint(20) NOT NULL,
  `learner_interaction_type_id` bigint(20) NOT NULL,
  PRIMARY KEY (`id`),
  KEY `FKc1cl3uvemcymmkbujvbfwomcg` (`game_registration_id`),
  KEY `FKakyfw3kohtvr182v4rj9jqxeg` (`learner_interaction_type_id
    `)
) ENGINE=MyISAM AUTO_INCREMENT=3108 DEFAULT CHARSET=utf8;
/*!40101 SET character_set_client = @saved_cs_client */;

--
-- Table structure for table `learner_interaction_type`
--

DROP TABLE IF EXISTS `learner_interaction_type`;
/*!40101 SET @saved_cs_client     = @@character_set_client */;
/*!40101 SET character_set_client = utf8 */;
CREATE TABLE `learner_interaction_type` (
  `id` bigint(20) NOT NULL AUTO_INCREMENT,
```

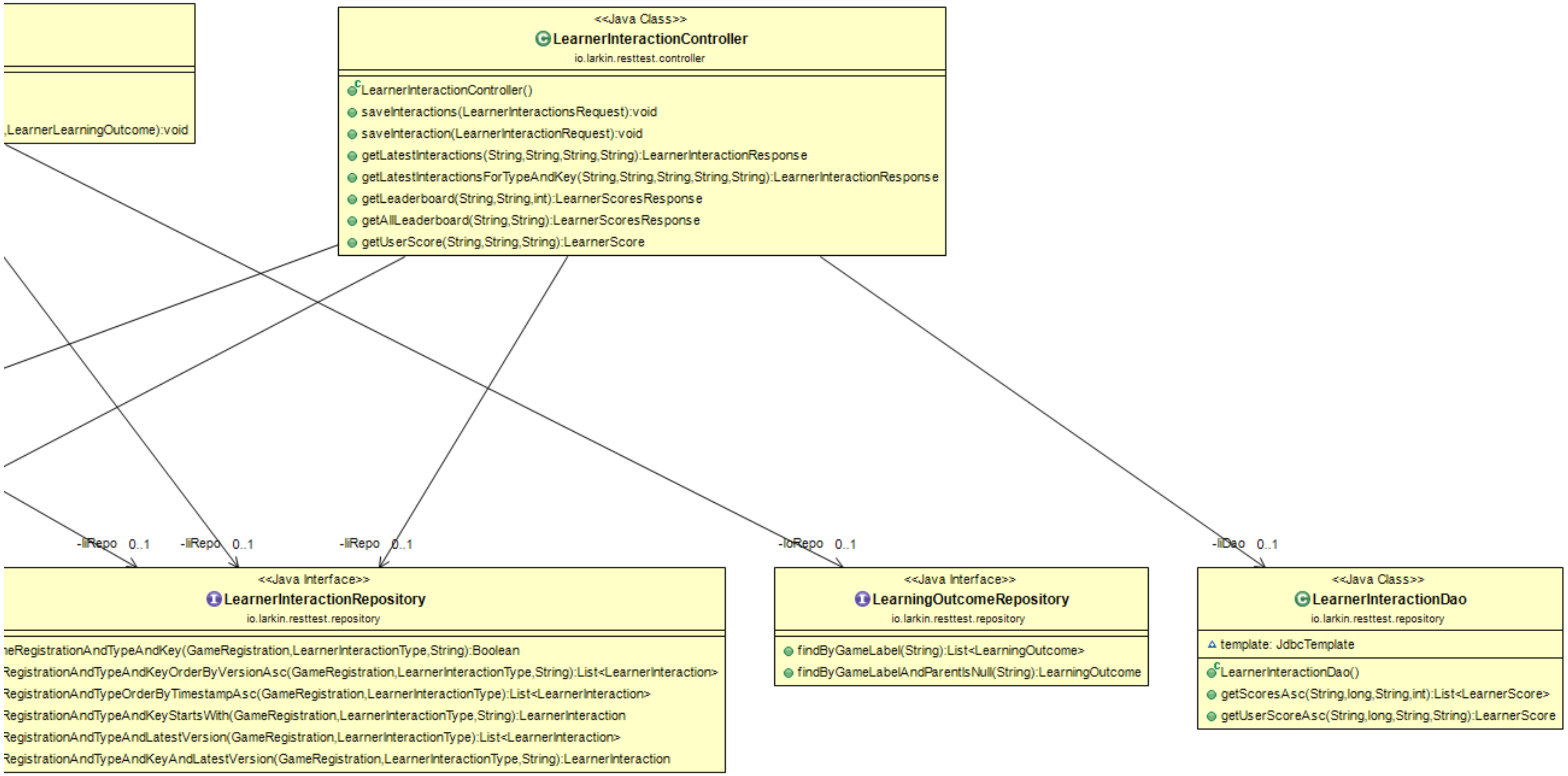
```
  `description` varchar(255) DEFAULT NULL,
  `name` varchar(255) DEFAULT NULL,
  PRIMARY KEY (`id`)
) ENGINE=MyISAM AUTO_INCREMENT=10 DEFAULT CHARSET=utf8;
/*!40101 SET character_set_client = @saved_cs_client */;

--
-- Table structure for table `learning_outcome`
--

DROP TABLE IF EXISTS `learning_outcome`;
/*!40101 SET @saved_cs_client     = @@character_set_client */;
/*!40101 SET character_set_client = utf8 */;
CREATE TABLE `learning_outcome` (
  `id` bigint(20) NOT NULL AUTO_INCREMENT,
  `description` varchar(255) DEFAULT NULL,
  `label` varchar(255) DEFAULT NULL,
  `game_id` bigint(20) DEFAULT NULL,
  `parent_id` bigint(20) DEFAULT NULL,
  `taxonomy_level_id` bigint(20) DEFAULT NULL,
  PRIMARY KEY (`id`),
  KEY `FK8cj9qy5js8ir1gq3dujf4iyyt` (`game_id`),
  KEY `FKpyjca8c82xxanxqq8215lhppw` (`parent_id`),
  KEY `FK64o82s88no03qhqvuvyli7ar4` (`taxonomy_level_id`)
) ENGINE=MyISAM AUTO_INCREMENT=12 DEFAULT CHARSET=utf8;
/*!40101 SET character_set_client = @saved_cs_client */;

--
-- Table structure for table `taxonomy`
--

DROP TABLE IF EXISTS `taxonomy`;
/*!40101 SET @saved_cs_client     = @@character_set_client */;
/*!40101 SET character_set_client = utf8 */;
CREATE TABLE `taxonomy` (
  `id` bigint(20) NOT NULL AUTO_INCREMENT,
  `description` varchar(255) DEFAULT NULL,
  `title` varchar(255) DEFAULT NULL,
  PRIMARY KEY (`id`)
) ENGINE=MyISAM AUTO_INCREMENT=2 DEFAULT CHARSET=utf8;
/*!40101 SET character_set_client = @saved_cs_client */;

--
-- Table structure for table `taxonomy_level`
--
```

```

DROP TABLE IF EXISTS `taxonomy_level`;
/*!40101 SET @saved_cs_client     = @@character_set_client */;
/*!40101 SET character_set_client = utf8 */;
CREATE TABLE `taxonomy_level` (
  `id` bigint(20) NOT NULL AUTO_INCREMENT,
  `description` varchar(255) DEFAULT NULL,
  `sequence` int(11) NOT NULL,
  `title` varchar(255) DEFAULT NULL,
  `taxonomy_id` bigint(20) DEFAULT NULL,
  PRIMARY KEY (`id`),
  KEY `FK1f8i7cip431ndlwun1fjd21oa` (`taxonomy_id`)
) ENGINE=MyISAM AUTO_INCREMENT=6 DEFAULT CHARSET=utf8;
/*!40101 SET character_set_client = @saved_cs_client */;
/*!40103 SET TIME_ZONE=@OLD_TIME_ZONE */;

/*!40101 SET SQL_MODE=@OLD_SQL_MODE */;
/*!40014 SET FOREIGN_KEY_CHECKS=@OLD_FOREIGN_KEY_CHECKS */;
/*!40014 SET UNIQUE_CHECKS=@OLD_UNIQUE_CHECKS */;
/*!40101 SET CHARACTER_SET_CLIENT=@OLD_CHARACTER_SET_CLIENT */;
/*!40101 SET CHARACTER_SET_RESULTS=@OLD_CHARACTER_SET_RESULTS */;
/*!40101 SET COLLATION_CONNECTION=@OLD_COLLATION_CONNECTION */;
/*!40111 SET SQL_NOTES=@OLD_SQL_NOTES */;

-- Dump completed on 2018-07-20 11:37:12
```

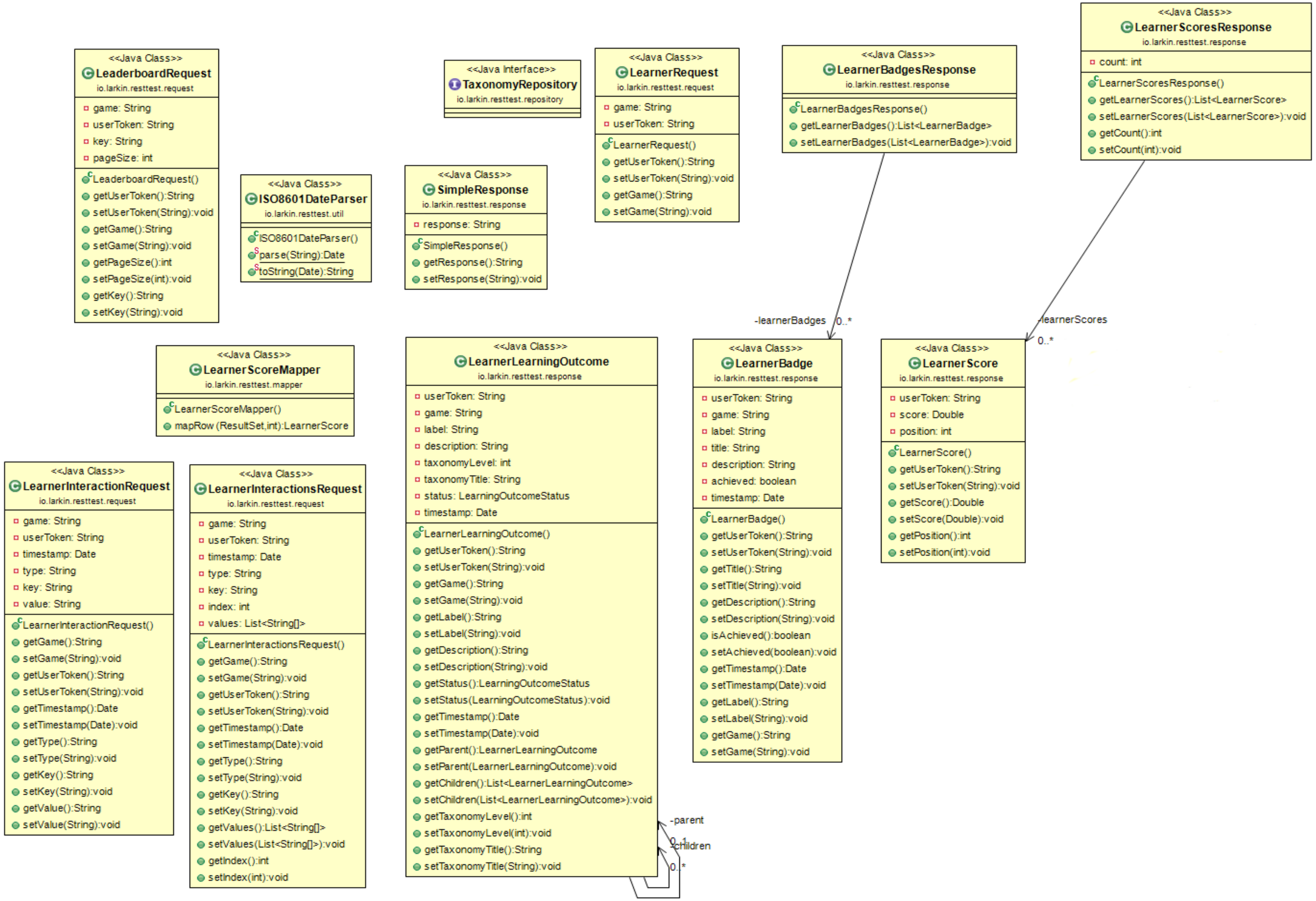
D.3 API UML Diagram

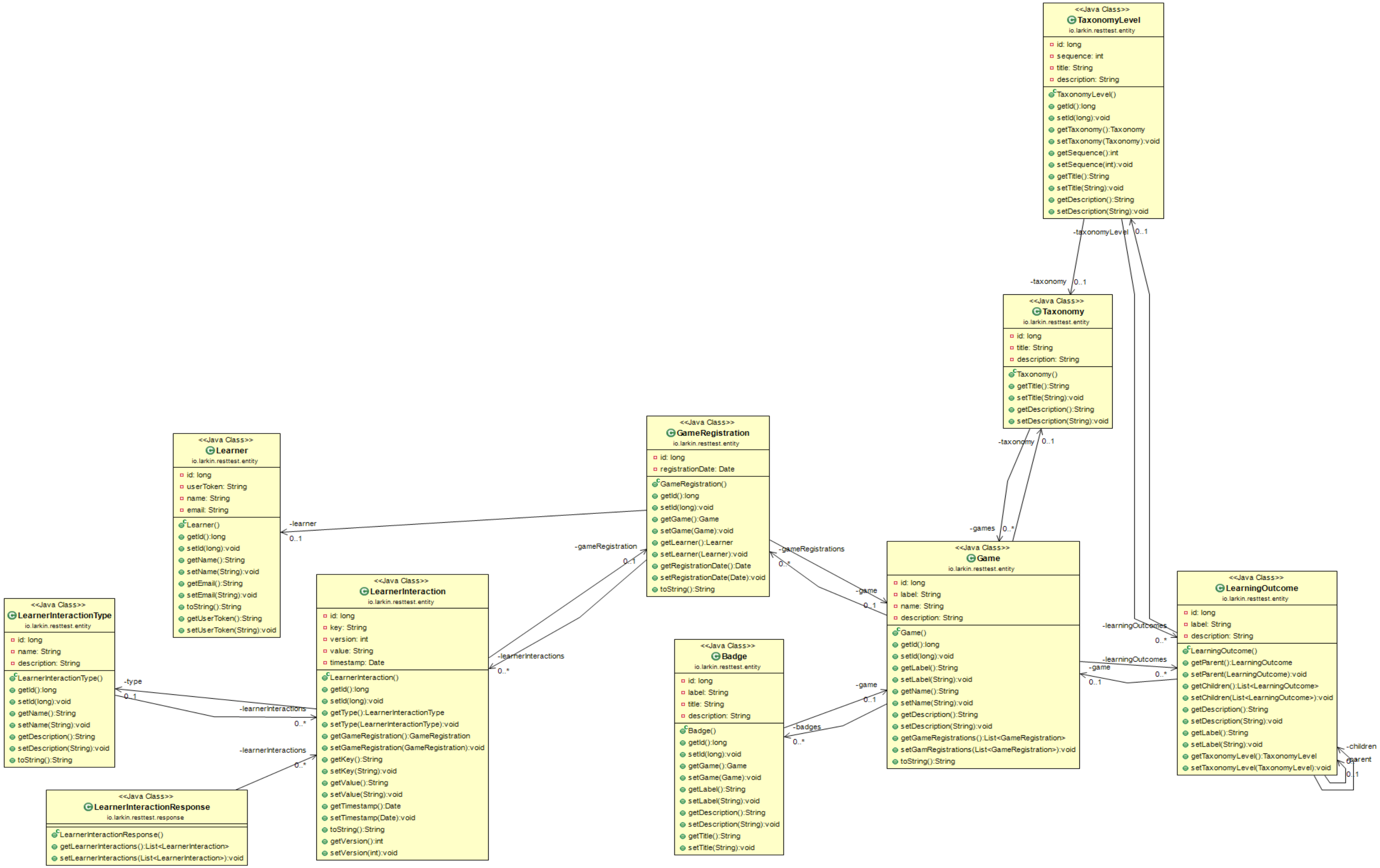
The UML diagram showing all of the components (classes) in the API application is split over four pages, beginning overleaf. It shows the associations between classes—for example, the `GameRegistrationRepository` has an association with the three controllers. The final page of the diagram illustrates, for example, the possible compositions of a `LearnerInteraction`—it can be the award of a `Badge`, the completion of a `LearningOutcome` (which is associated with a `Taxonomy`), or other miscellaneous discrete types not explicitly modelled in the diagram (such as scores and an audit trail).


<<Java Class>>
LearnerController
io.larkin.resttest.controller
LearnerController()
saveObject(LearnerRequest):void
gameRegExists(String,String):SimpleResponse
getLearnerBadges(String,String):List<LearnerBadge>
<<Java Class>>
LearningOutcomeController
io.larkin.resttest.controller
LearningOutcomeController()
getGameLearningOutcomesByUser(String,String):LearnerLearningOutcome
fillLLOResponse(GameRegistration,LearnerInteractionType,LearningOutcome,
-lRepo 0..1
-bRepo 0..1
-gRepo 0..1
-grRepo 0..1
-grRepo 0..1
-grRepo 0..1
-litRepo 0..1
-litRepo 0..1
-litRepo 0..1
<<Java Interface>>
LearnerRepository
io.larkin.resttest.repository
findByUserToken(String):Learner
existsByUserToken(String):Boolean
<<Java Interface>>
BadgeRepository
io.larkin.resttest.repository
findByGameLabel(String):List<Badge>
<<Java Interface>>
GameRepository
io.larkin.resttest.repository
findByLabel(String):Game
<<Java Interface>>
GameRegistrationRepository
io.larkin.resttest.repository
findByGameLabelAndLearnerUserToken(String,String):GameRegistration
findByGameAndLearner(Game,Learner):GameRegistration
<<Java Interface>>
LearnerInteractionTypeRepository
io.larkin.resttest.repository
findByName(String):LearnerInteractionType
existsByGam
findByGameR
findByGameR
findByGameR
findByGameR
findByGameR



,LearnerLearningOutcome):void
<<Java Class>>
LearnerInteractionController
io.larkin.resttest.controller
LearnerInteractionController()
saveInteractions(LearnerInteractionsRequest):void
saveInteraction(LearnerInteractionRequest):void
getLatestInteractions(String,String,String,String):LearnerInteractionResponse
getLatestInteractionsForTypeAndKey(String,String,String,String,String):LearnerInteractionResponse
getLeaderboard(String,String,int):LearnerScoresResponse
getAllLeaderboard(String,String):LearnerScoresResponse
getUserScore(String,String,String):LearnerScore
-liRepo 0..1
-liRepo 0..1
-liRepo 0..1
-loRepo 0..1
-liDao 0..1
<<Java Interface>>
LearnerInteractionRepository
io.larkin.resttest.repository
eRegistrationAndTypeAndKey(GameRegistration,LearnerInteractionType,String):Boolean
RegistrationAndTypeAndKeyOrderByVersionAsc(GameRegistration,LearnerInteractionType,String):List<LearnerInteraction>
RegistrationAndTypeOrderByTimestampAsc(GameRegistration,LearnerInteractionType):List<LearnerInteraction>
RegistrationAndTypeAndKeyStartsWith(GameRegistration,LearnerInteractionType,String):LearnerInteraction
RegistrationAndTypeAndLatestVersion(GameRegistration,LearnerInteractionType):List<LearnerInteraction>
RegistrationAndTypeAndKeyAndLatestVersion(GameRegistration,LearnerInteractionType,String):LearnerInteraction
<<Java Interface>>
LearningOutcomeRepository
io.larkin.resttest.repository
findByGameLabel(String):List<LearningOutcome>
findByGameLabelAndParentIsNull(String):LearningOutcome
<<Java Class>>
LearnerInteractionDao
io.larkin.resttest.repository
template: JdbcTemplate
LearnerInteractionDao()
getScoresAsc(String,long,String,int):List<LearnerScore>
getUserScoreAsc(String,long,String,String):LearnerScore


<<Java Class>>
LeaderboardRequest
io.larkin.resttest.request
game: String
userToken: String
key: String
pageSize: int
LeaderboardRequest()
getUserToken():String
setUserToken(String):void
getGame():String
setGame(String):void
getPageSize():int
setPageSize(int):void
getKey():String
setKey(String):void
<<Java Class>>
ISO8601DateParser
io.larkin.resttest.util
ISO8601DateParser()
parse(String):Date
toString(Date):String
<<Java Interface>>
TaxonomyRepository
io.larkin.resttest.repository
<<Java Class>>
SimpleResponse
io.larkin.resttest.response
response: String
SimpleResponse()
getResponse():String
setResponse(String):void
<<Java Class>>
LearnerRequest
io.larkin.resttest.request
game: String
userToken: String
LearnerRequest()
getUserToken():String
setUserToken(String):void
getGame():String
setGame(String):void
<<Java Class>>
LearnerBadgesResponse
io.larkin.resttest.response
LearnerBadgesResponse()
getLearnerBadges():List<LearnerBadge>
setLearnerBadges(List<LearnerBadge>):void
<<Java Class>>
LearnerScoresResponse
io.larkin.resttest.response
count: int
LearnerScoresResponse()
getLearnerScores():List<LearnerScore>
setLearnerScores(List<LearnerScore>):void
getCount():int
setCount(int):void
-learnerBadges
0..*
-learnerScores
0..*
<<Java Class>>
LearnerScoreMapper
io.larkin.resttest.mapper
LearnerScoreMapper()
mapRow(ResultSet,int):LearnerScore
<<Java Class>>
LearnerLearningOutcome
io.larkin.resttest.response
userToken: String
game: String
label: String
description: String
taxonomyLevel: int
taxonomyTitle: String
status: LearningOutcomeStatus
timestamp: Date
LearnerLearningOutcome()
getUserToken():String
setUserToken(String):void
getGame():String
setGame(String):void
getLabel():String
setLabel(String):void
getDescription():String
setDescription(String):void
getStatus():LearningOutcomeStatus
setStatus(LearningOutcomeStatus):void
getTimestamp():Date
setTimestamp(Date):void
getParent():LearnerLearningOutcome
setParent(LearnerLearningOutcome):void
getChildren():List<LearnerLearningOutcome>
setChildren(List<LearnerLearningOutcome>):void
getTaxonomyLevel():int
setTaxonomyLevel(int):void
getTaxonomyTitle():String
setTaxonomyTitle(String):void
-parent
0..1
-children
0..*
<<Java Class>>
LearnerBadge
io.larkin.resttest.response
userToken: String
game: String
label: String
title: String
description: String
achieved: boolean
timestamp: Date
LearnerBadge()
getUserToken():String
setUserToken(String):void
getTitle():String
setTitle(String):void
getDescription():String
setDescription(String):void
isAchieved():boolean
setAchieved(boolean):void
getTimestamp():Date
setTimestamp(Date):void
getLabel():String
setLabel(String):void
getGame():String
setGame(String):void
<<Java Class>>
LearnerScore
io.larkin.resttest.response
userToken: String
score: Double
position: int
LearnerScore()
getUserToken():String
setUserToken(String):void
getScore():Double
setScore(Double):void
getPosition():int
setPosition(int):void
<<Java Class>>
LearnerInteractionRequest
io.larkin.resttest.request
game: String
userToken: String
timestamp: Date
type: String
key: String
value: String
LearnerInteractionRequest()
getGame():String
setGame(String):void
getUserToken():String
setUserToken(String):void
getTimestamp():Date
setTimestamp(Date):void
getType():String
setType(String):void
getKey():String
setKey(String):void
getValue():String
setValue(String):void
<<Java Class>>
LearnerInteractionsRequest
io.larkin.resttest.request
game: String
userToken: String
timestamp: Date
type: String
key: String
index: int
values: List<String[]>
LearnerInteractionsRequest()
getGame():String
setGame(String):void
getUserToken():String
setUserToken(String):void
getTimestamp():Date
setTimestamp(Date):void
getType():String
setType(String):void
getKey():String
setKey(String):void
getValues():List<String[]>
setValues(List<String[]>):void
getIndex():int
setIndex(int):void


<<Java Class>>
TaxonomyLevel
io.larkin.resttest.entity
id: long
sequence: int
title: String
description: String
TaxonomyLevel()
getId():long
setId(long):void
getTaxonomy():Taxonomy
setTaxonomy(Taxonomy):void
getSequence():int
setSequence(int):void
getTitle():String
setTitle(String):void
getDescription():String
setDescription(String):void
-taxonomyLevel
0..1
-taxonomy
0..1
<<Java Class>>
Taxonomy
io.larkin.resttest.entity
id: long
title: String
description: String
Taxonomy()
getTitle():String
setTitle(String):void
getDescription():String
setDescription(String):void
-taxonomy
0..1
-games
0..*
<<Java Class>>
GameRegistration
io.larkin.resttest.entity
id: long
registrationDate: Date
GameRegistration()
getId():long
setId(long):void
getGame():Game
setGame(Game):void
getLearner():Learner
setLearner(Learner):void
getRegistrationDate():Date
setRegistrationDate(Date):void
toString():String
<<Java Class>>
Learner
io.larkin.resttest.entity
id: long
userToken: String
name: String
email: String
Learner()
getId():long
setId(long):void
getName():String
setName(String):void
getEmail():String
setEmail(String):void
getUserToken():String
setUserToken(String):void
-learner
0..1
-gameRegistration
0..1
-gameRegistrations
0..*
-game
0..1
<<Java Class>>
Game
io.larkin.resttest.entity
id: long
label: String
name: String
description: String
Game()
getId():long
setId(long):void
getLabel():String
setLabel(String):void
getName():String
setName(String):void
getDescription():String
setDescription(String):void
getGameRegistrations():List<GameRegistration>
setGamRegistrations(List<GameRegistration>):void
toString():String
-learningOutcomes
0..*
-learningOutcomes
-game
0..*
0..1
<<Java Class>>
LearningOutcome
io.larkin.resttest.entity
id: long
label: String
description: String
LearningOutcome()
getParent():LearningOutcome
setParent(LearningOutcome):void
getChildren():List<LearningOutcome>
setChildren(List<LearningOutcome>):void
getDescription():String
setDescription(String):void
getLabel():String
setLabel(String):void
getTaxonomyLevel():TaxonomyLevel
setTaxonomyLevel(TaxonomyLevel):void
-children
-parent
0..1
<<Java Class>>
LearnerInteraction
io.larkin.resttest.entity
id: long
key: String
version: int
value: String
timestamp: Date
LearnerInteraction()
getId():long
setId(long):void
getType():LearnerInteractionType
setType(LearnerInteractionType):void
getGameRegistration():GameRegistration
setGameRegistration(GameRegistration):void
getKey():String
setKey(String):void
getValue():String
setValue(String):void
getTimestamp():Date
setTimestamp(Date):void
toString():String
getVersion():int
setVersion(int):void
-learnerInteractions
0..*
<<Java Class>>
LearnerInteractionType
io.larkin.resttest.entity
id: long
name: String
description: String
LearnerInteractionType()
getId():long
setId(long):void
getName():String
setName(String):void
getDescription():String
setDescription(String):void
toString():String
-type
0..1
-learnerInteractions
0..*
-learnerInteractions
0..*
<<Java Class>>
LearnerInteractionResponse
io.larkin.resttest.response
LearnerInteractionResponse()
getLearnerInteractions():List<LearnerInteraction>
setLearnerInteractions(List<LearnerInteraction>):void
<<Java Class>>
Badge
io.larkin.resttest.entity
id: long
label: String
title: String
description: String
Badge()
getId():long
setId(long):void
getGame():Game
setGame(Game):void
getLabel():String
setLabel(String):void
getDescription():String
setDescription(String):void
getTitle():String
setTitle(String):void
-game
0..1
-badges
0..*

D.4 Spring Boot / Java Source Code

D.4.1 API

The source code for the API (written in Java and using the Spring framework) can be viewed at the following website:
https://dlarkinc.github.io/phd-rest-test/

The main Java classes can be found at:
https://github.com/dlarkinc/phd-rest-test/tree/master/src/main/java/io/larkin/resttest

D.4.2 Dashboard

The source code for the dashboard (also written in Java and using the Spring framework) can be viewed at the following website:
https://dlarkinc.github.io/phd-dashboard/

The classes can be found at:
https://github.com/dlarkinc/phd-dashboard/tree/master/src/main/java/io/larkin/phddash

The Thymeleaf web templates can be found at:
https://github.com/dlarkinc/phd-dashboard/tree/master/src/main/resources/templates

D.5 The Learner Study Data Analysis

D.5.1 Data Cleaning SQL

D.5.1.1 Remove Non-participant Data

Listing D.2: Remove Non-participant Data

```
DELETE
  FROM learner_interaction
 WHERE game_registration_id NOT IN
        (SELECT gr.id
           FROM game_registration gr, learner l
          WHERE gr.learner_id = l.id
            AND l.letter BETWEEN 'A' AND 'T')
        );
```

Result:

Message	Duration / Fetch
467 row(s) affected	*0.031 sec*

D.5.2 R Scripts

All R scripts used for statistical analysis and to generate plots and charts can be found at the public GitHub repository: https://github.com/dlarkinc/PhD_R

Appendix E

Tabular Data

Table E.1: Participant Gameplay Durations

Participant	Duration (sec)
A	1866
B	1305
C	906
D	3038
E	1605
F	1947
G	1351
I	1816
J	1548
K	1597
L	769
M	1765
N	2858
O	2574
P	1969
Q	1223
R	2045
S	2706
T	1994
Mean	1835.9
Std. Dev.	622.97

Table E.2: Participant Engagement with Examples

Participant	Duration 1 (s)	Duration 2 (s)	Teleports 1	Grabs 1	Teleports 2	Grabs 2
A	195	124				
B	103	67				
C	93	42				
D	327	272				
E	218	217				
F	231	164				
G	217	142				
I	162	83	16	2	7	0
J	148	88	3	0	5	0
K	197	99	5	0	4	0
L	81	101	4	2	2	0
M	272	92	9	12	2	0
N	295	251	1	6	2	0
O	289	159	3	6	4	0
P	260	225	1	6	3	0
Q	203	112	3	5	2	0
R	321	264	8	19	14	19
S	369	130	9	4	2	0
T	212	162	4	2	2	0

Table E.3: Statistics for Likert Item Responses in Section B to F (Scale 1 - 5)

Item	Mean	SD	N
B1	4.0	1.05	20
B2	4.3	0.98	20
B3	3.9	0.85	20
B4	4.5	0.76	20
C1	4.8	0.55	20
C2	4.3	0.81	20
C3	4.4	1.19	20
D1	4.5	0.61	20
D2	4.4	0.99	20
E1	4.1	0.91	20
E2	4.2	0.72	20
E3	4.3	0.73	20
E4	4.0	1.21	20
F1	4.2	0.91	20
F2	4.5	0.51	20
F3	4.8	0.55	20
F4	3.8	1.18	20
F5	4.5	0.83	20
F6	4.2	1.09	20
F7	4.3	1.08	20
F8	4.4	0.89	20
F9	4.0	0.94	20

Note: For the text associated with each item, refer to Appendix A.6 and A.7. Negative questions (where 5 indicates strong disagreement) have been reverse coded.

Table E.4: Statistics for Likert Item Responses in Sections G to I (Scale 1 - 5)

Item	Mean	SD	N
G1	4.5	0.60	20
G2	4.2	0.41	20
G3	4.5	0.83	20
H2	4.1	1.04	13
H3	3.5	1.05	13
H4	3.9	0.95	13
H5	3.8	1.24	13
H6	2.9	1.38	13
I1	4.5	0.69	20
I2	4.2	0.85	20
I3	4.5	0.76	20
I4	4.0	1.10	20
I5	4.6	0.67	20
I6	4.4	0.89	20
I7	4.2	1.11	20
I8	4.4	0.76	20
I9	4.6	0.75	20
I10	4.4	1.05	20
I11	4.3	0.59	20
I12	4.3	0.81	20
I13	4.3	0.59	20
I14	4.6	0.49	20
I15	4.1	0.86	13

Note: For the text associated with each item, refer to Appendix A.6 and A.7. Negative questions (where 5 indicates strong disagreement) have been reverse coded.

Table E.5: Profiles Provided by Respondents to the Practitioner Survey

VR lecturing and research.
I'm head of [a TEL department] with responsibility for developing and managing the institute's online distance programmes, sustaining and extending exploratory research into the enhancement and enrichment of the teaching and learning process through technology, and supporting the mainstream use of technology enhanced learning across the institute.
Instructional Designer. E-Learning: Project scoping, TNA, LO, Course outlines, Design, Development.
Third Level Accounting Lecturer on non-traditional business programmes. Teaching & assessment are entirely PC based. Interest in research related to gamification of introductory accounting education.
Technical officer, deals with supporting online programme delivery, research into new forms of technology enhanced learning, etc
Lecturer in French for Business - interested in GBL Currently researching the area regarding motivation and learning in GBL
Research in the areas of technology enhanced learning, game based learning, instructional design and development. Design and development of media and resources for teaching and learning.
Researcher, interdisciplinary but recently focussing on game-based learning.
Full stack software engineering, data analysis, system architecture design. Technical consulting in the areas of knowledge engineering, educational technology, game-based learning, adaptive and personalised systems, decision support systems, and the use of machine learning to support automated learning content creation.
Associate Lecturer at the University of [Redacted], teaching and supervision dissertations on the [postgraduate education course focused on the digital], specialising on the subjects assessment, games-based learning and the psychology of learning.
Owner of e-learning company that provides digital learning solutions. I scope and oversee all projects within the company including ascertaining the effectiveness of the solutions we provide i.e. on the job impact, ROI, customer satisfaction etc.
Instructional Designer/e-learning Developer - In my role I work with sme's to develop online educational content. I mostly use Articulate Storyline. Within the learning we sometimes use game based training

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